Cryogenic

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11th June 2019
Gravitational Wave Challenges and Cosmology
@International Institute of Physics , Natal, Brazil

Abstract

Why do we adopt cryogenics (cooled mirrors) to detect gravitational wave ?

(1)Merits : Reduction of thermal noise
and so on

(2) How to cool down

Contents

1. Introduction
2. Thermal noise
3. Other merits
4. How to cool down
5. Summary

1.Introduction

List of cryogenic interferometric gravitational wave detectors

Constructed

CLIO (Japan, Sapphire, 100m)

KAGRA (Japan, Sapphire, 3km)

Future plan

Voyager (U.S.A., Silicon, 4km, LIGO facility, Odylio Aguiar in this afternoon)

Einstein Telescope (Europe, Silicon, 10km)

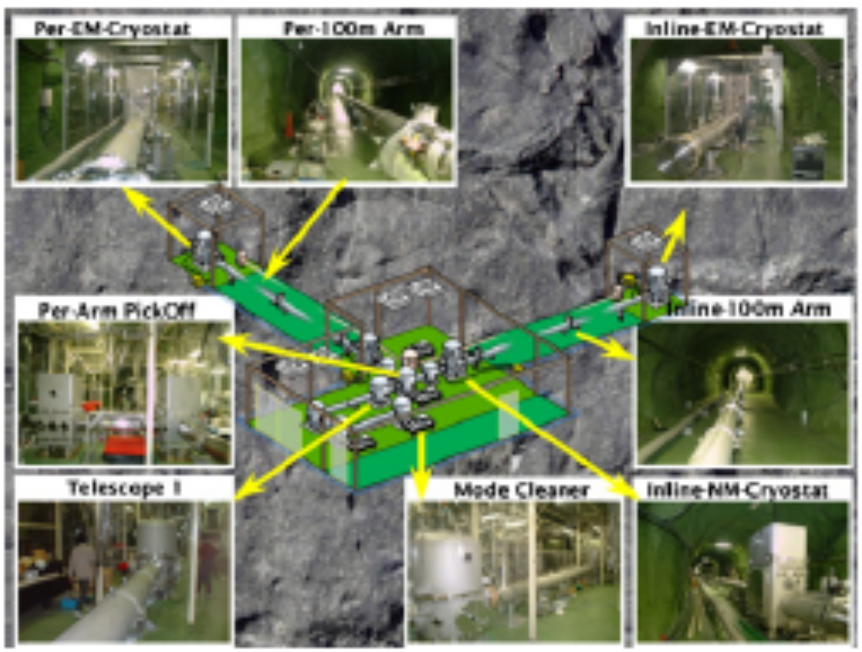
Cosmic Explorer (U.S.A., Silicon, 40km) (Michele Punturo in this afternoon)

1.Introduction

List of cryogenic interferometric gravitational wave detectors

Constructed

CLIO (Japan, Sapphire, 100m)



K.Agatsuma et al., Physical Review Letters 104 (2010) 040602.
T. Uchiyama et a;., Physical Review Letters 108 (2012) 141101.

1.Introduction

List of cryogenic interferometric gravitational wave

e, 100m)

hire, 3km, observation starts

on, 4km, LIGO facility)

urope, Silicon, 10km)

.A., Silicon, 40km)

1.Introduction

List of cryogenic interferometric gravitational wave

**There are 4 mirrors.
3 of them are cooled down. The last one will be cooled down within two weeks.**

on, 4km, LIGO facility)

urope, Silicon, 10km)

.A., Silicon, 40km)

1.Introduction

List of cryogenic interferometric gravitational wave

Commissioning with cooled mirror is in progress.

Engineering run of a 3km cavity on 8th of June 2019. Duty cycle is 95% at least.

.A., Silicon, 40km)

1.Introduction

List of cryogenic interferometric gravitational wave

Fabian Arellano, Enzo Tapia, Koki Okutomi will present KAGRA vibration isolation system tomorrow afternoon.

on, 4km, LIGO facility)

urope, Silicon, 10km)

.A., Silicon, 40km)

2. Thermal noise

Motivation of cryonic interferometer is reduction of thermal noise.

Story is not so simple …

Energy equipartition theorem

$$< x^2 > = k_B T/2$$

We are interested with power spectrum density in frequency region. Our observation band is between 10Hz and 10kHz. x^2 is integral of power spectrum density in all frequency region.

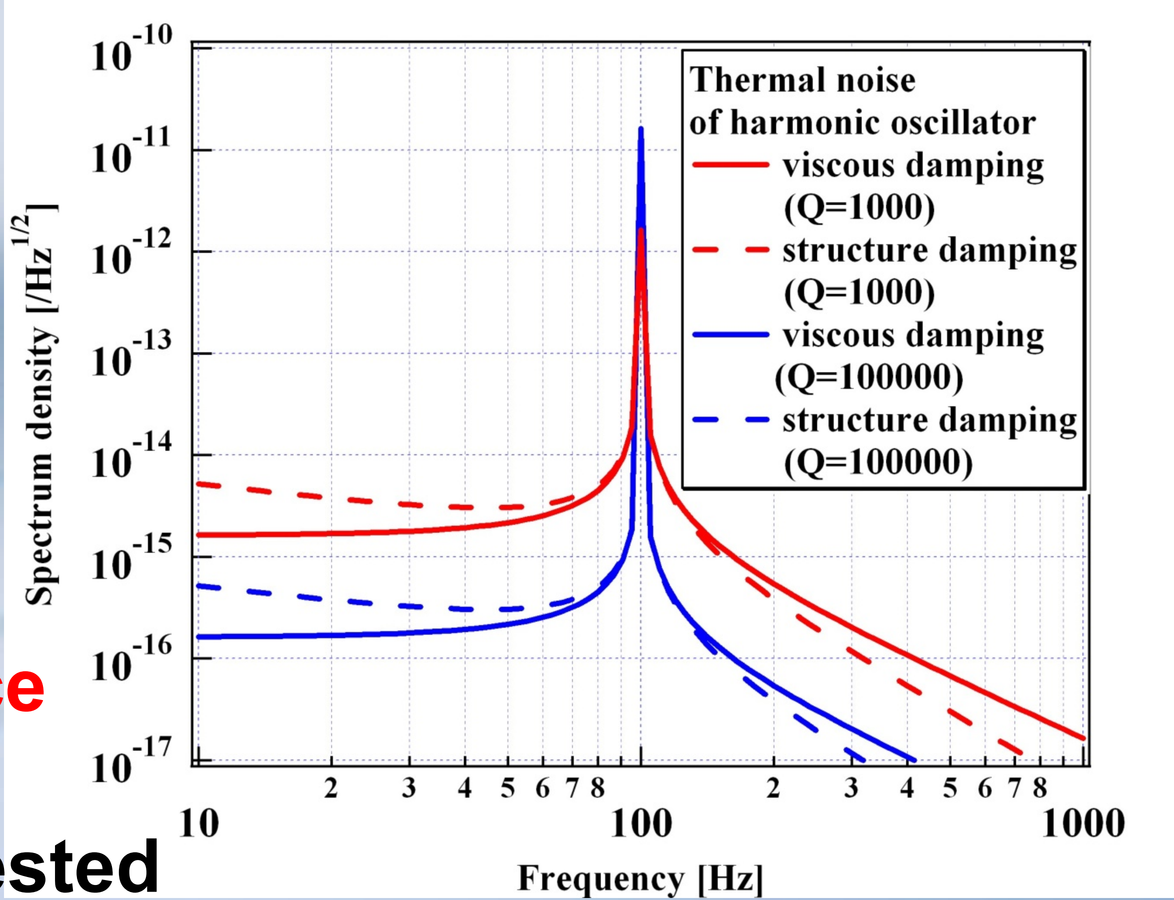
2. Thermal noise

Spectrum density of thermal noise of harmonic oscillator

Q-value :
Magnitude of loss

Higher Q is smaller loss.

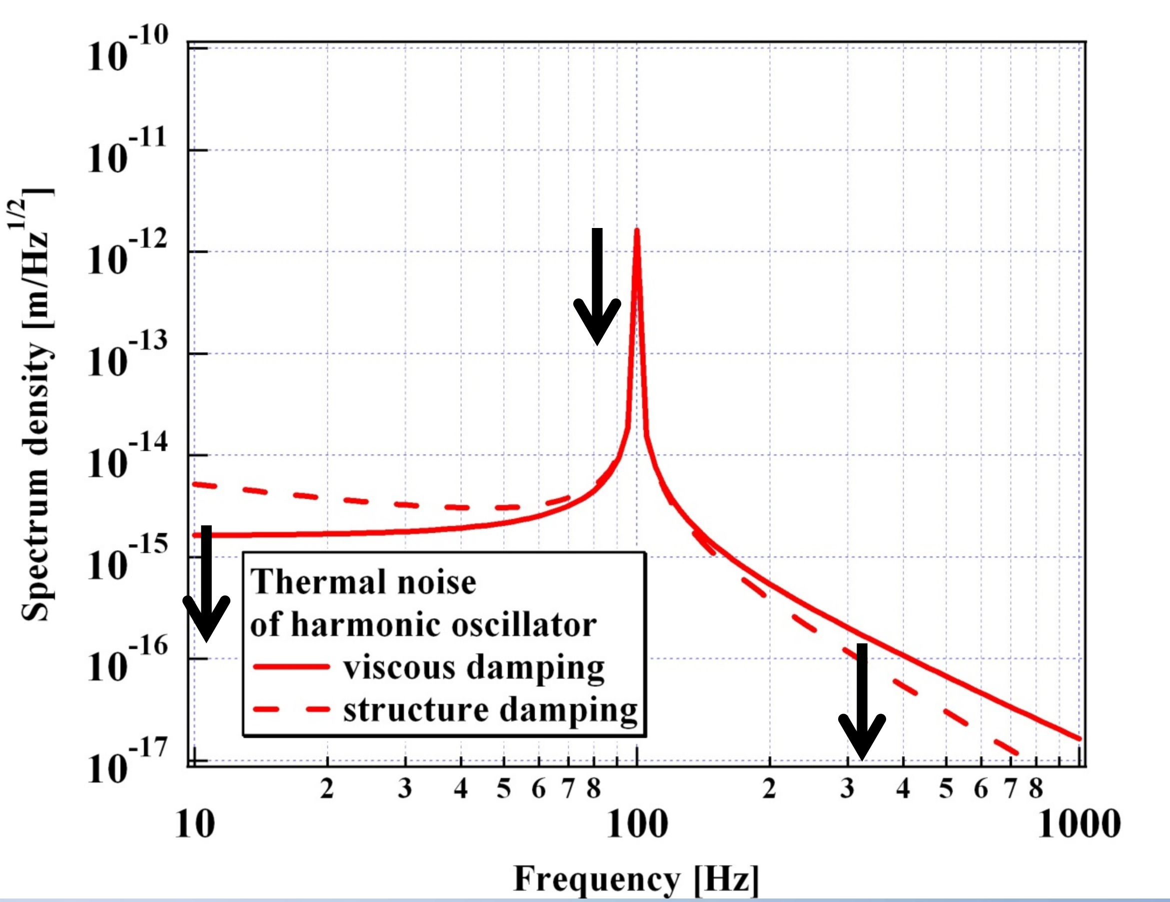
Higher Q is smaller off resonance thermal noise and better. We interested with off resonance.



2. Thermal noise

Spectrum density of thermal noise of harmonic oscillator

When Q is independent of temperature, power spectrum density in all frequency region is smaller at lower temperature.



2. Thermal noise

Amplitude of thermal noise (off resonance) is proportional to

$$(T/Q)^{1/2}$$

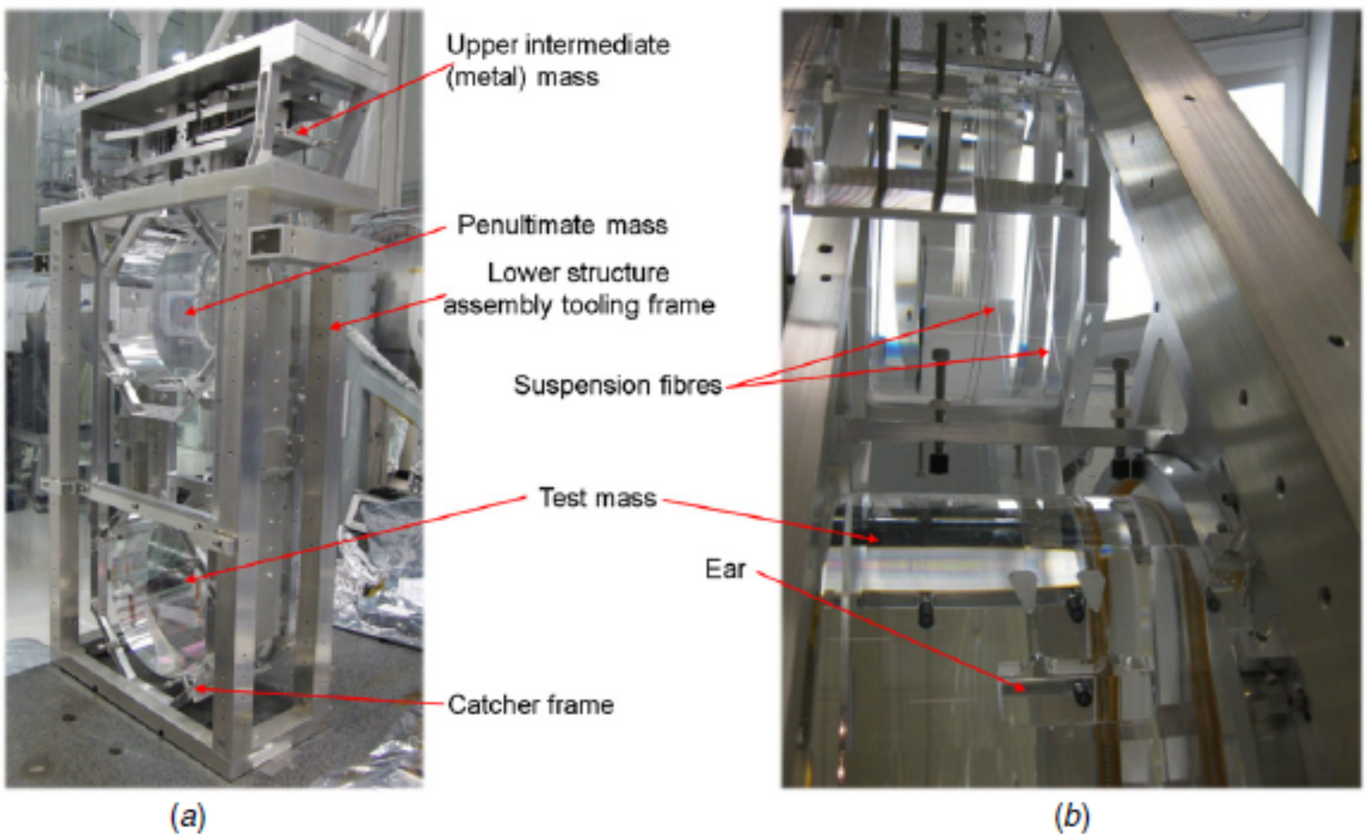
In general, Q-value depends on T (temperature).

We must investigate how dissipation depends on temperature in cryogenic region.

2. Thermal noise

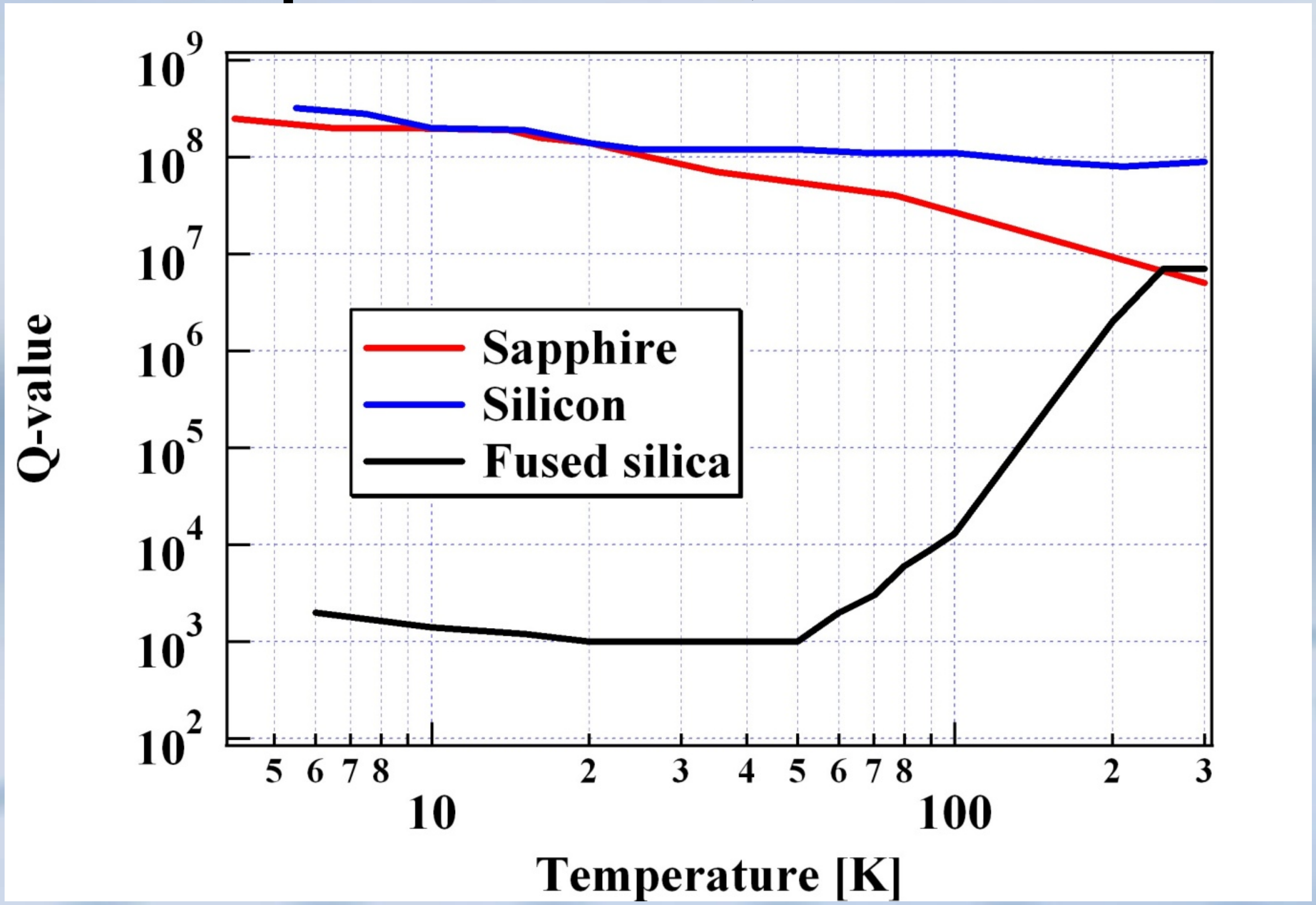
Room temperature second generation interferometer
Fused silica mirror suspended by fused silica fibers

Class. Quantum Grav. **29** (2012) 035003 A V Cumming *et al*



2. Thermal noise

Temperature dependence of Q values

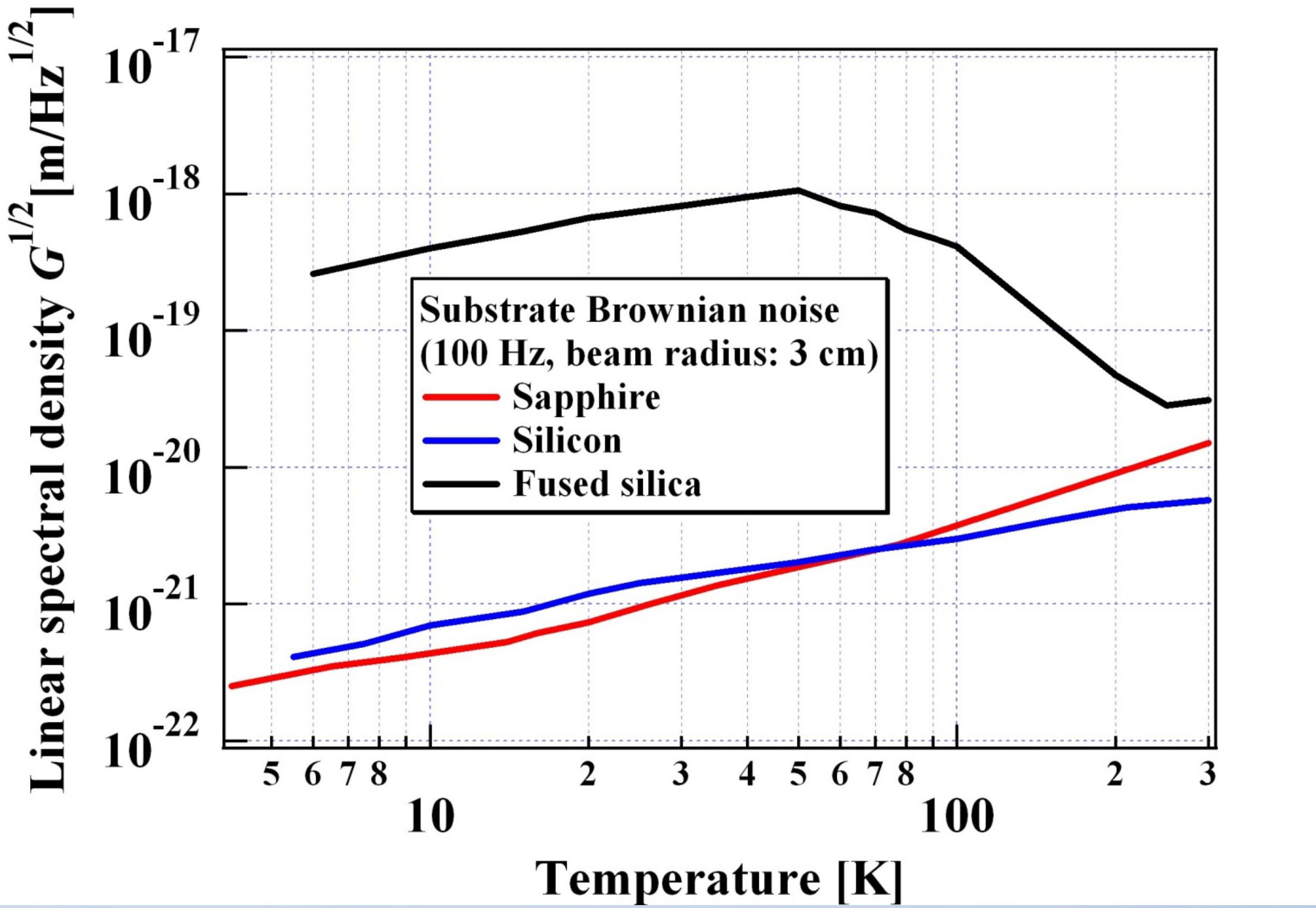


T. Uchiyama *et al*., Physics Letters A 261 (1999) 5-11.
R. Nawrodt *et al.,* Journal of Physics: Conference Series 122 (2008) 012008.
C. Schwarz *et al.,* 2009 Proceedings of ICEC22-ICMC2008.

2. Thermal noise

Temperature dependence of $(T/Q)^{1/2}$

$(T/Q)^{1/2}$



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C. Schwarz *et al.,* 2009 Proceedings of ICEC22-ICMC2008.

2. Thermal noise

Important message

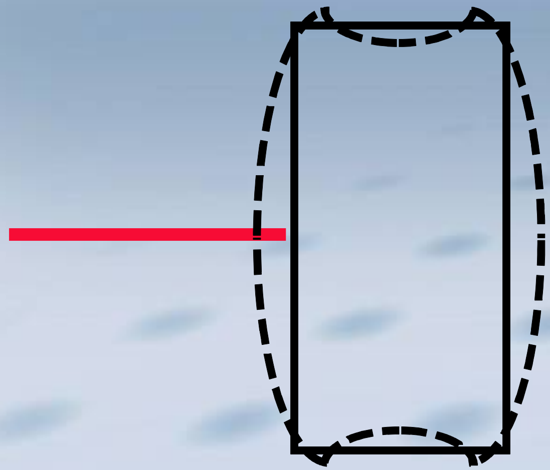
We can not use fused silica
for cryogenic interferometer.

New material (Sapphire, Silicon) is necessary for mirror substrate and fibers to suspend mirrors.
Challenge !

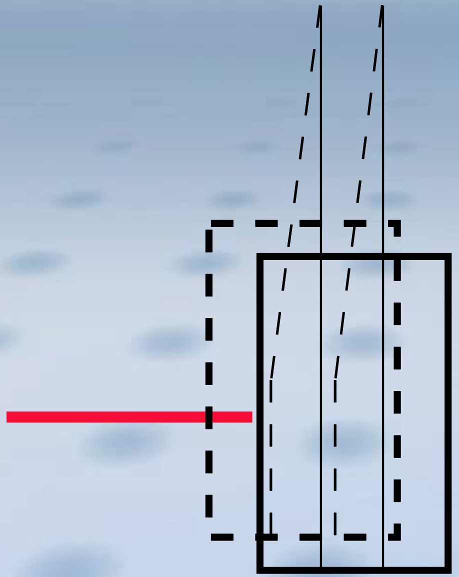
2. Thermal noise

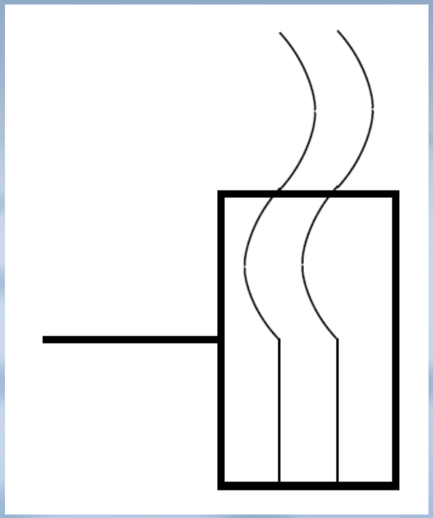
Thermal noise of mirror and suspension

Mirror



Suspension

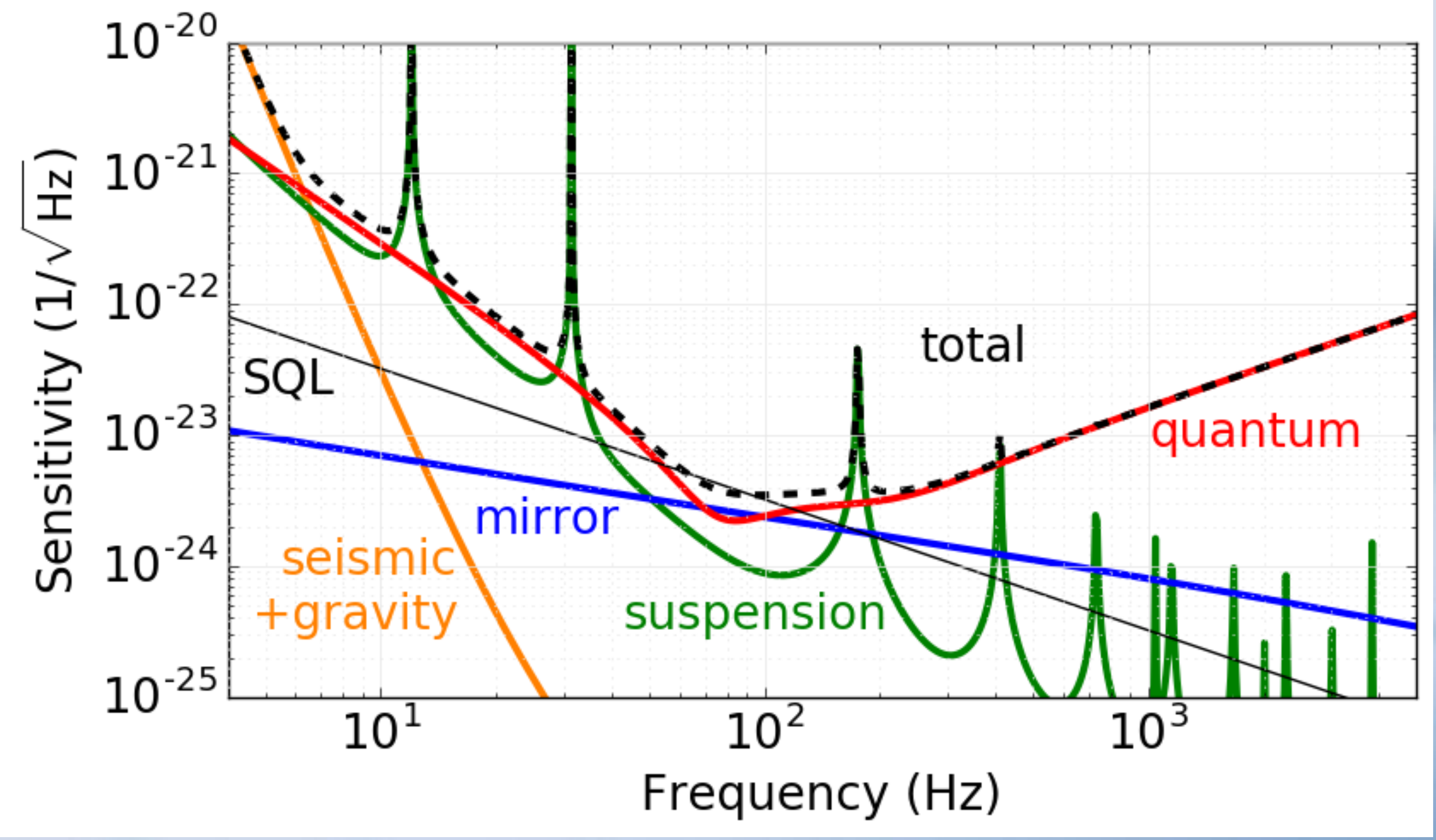




Pendulum **Violin modes**

2. Thermal noise

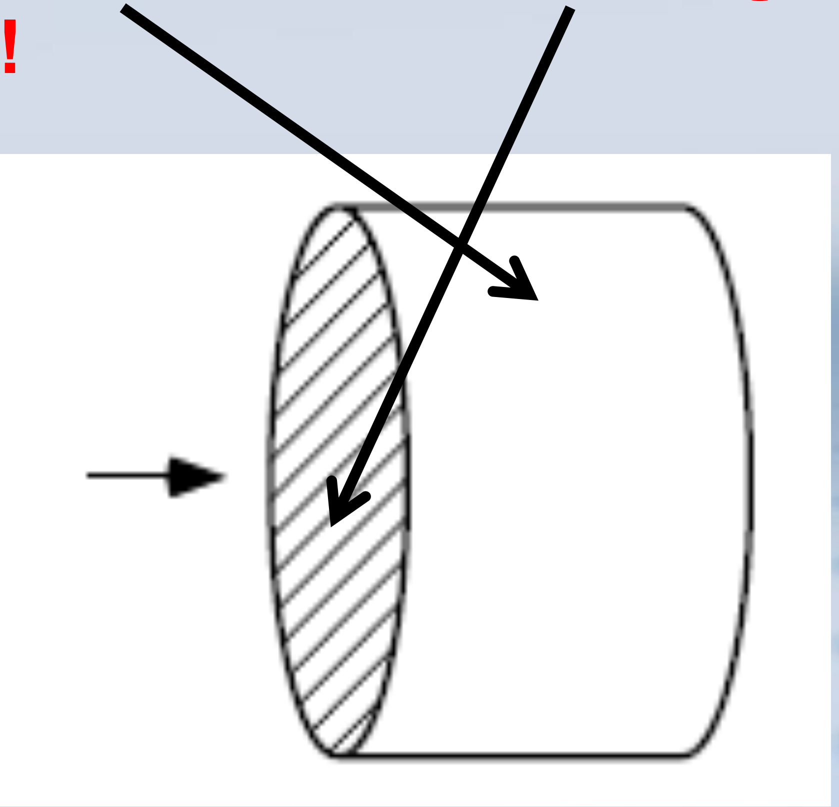
Thermal noise of mirror and suspension



2. Thermal noise

Thermal noise of **mirror**

Not only substrate but also coating must be taken into account !



Y. Levin, Physical Review D 57 (1998) 659.

2. Thermal noise

Mechanical dissipation generates thermal noise.

Loss in substrate and coating

Two kinds of loss : Structure, Thermoelastic

**Structure : Unknown frequency independent .
Measurement of Q-values is only reliable way.**

P.R. Saulson, Phys. Rev. D 42 (1990) 2437.

Thermoelastic : Coupling of temperature fluctuation and thermal expansion coefficient. We can calculate.

C. Zener, Phys. Rev. 52 (1937) 230; *ibid*. 53 (1938) 90.

2. Thermal noise

Mechanical dissipation generates thermal noise.

Loss in substrate and coating

Two kinds of loss : Structure, Thermoelastic

So, there are four kinds of loss (mirror thermal noise).

(1)Structure damping in substrate

(2)Thermoelastic damping in substrate

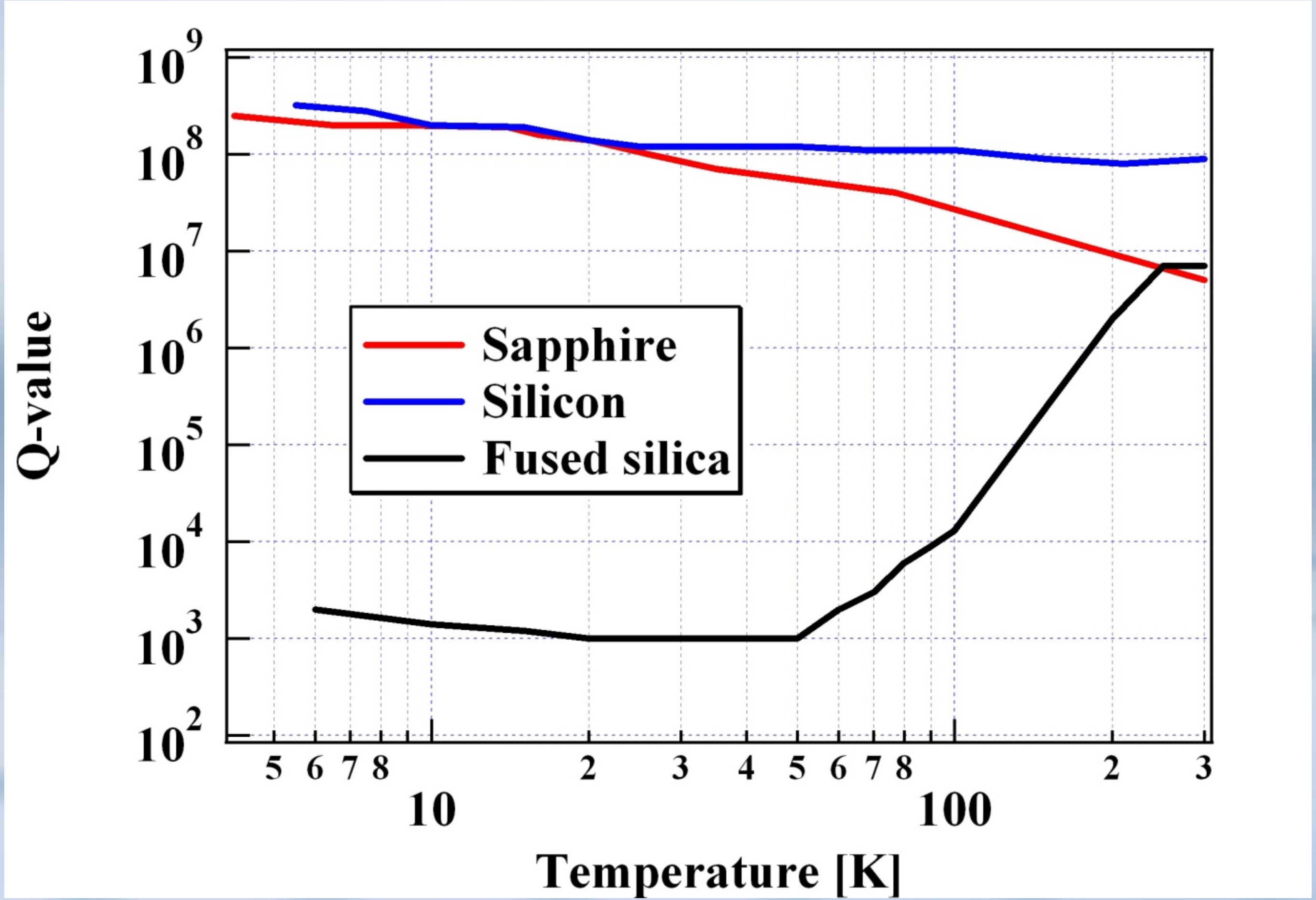
(3)Structure damping in coating

(4)Thermoelastic damping in coating

2. Thermal noise

Structure damping in substrate

Inverse numbth of loss strength



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R. Nawrodt *et al.,* Journal of Physics: Conference Series 122 (2008) 012008.
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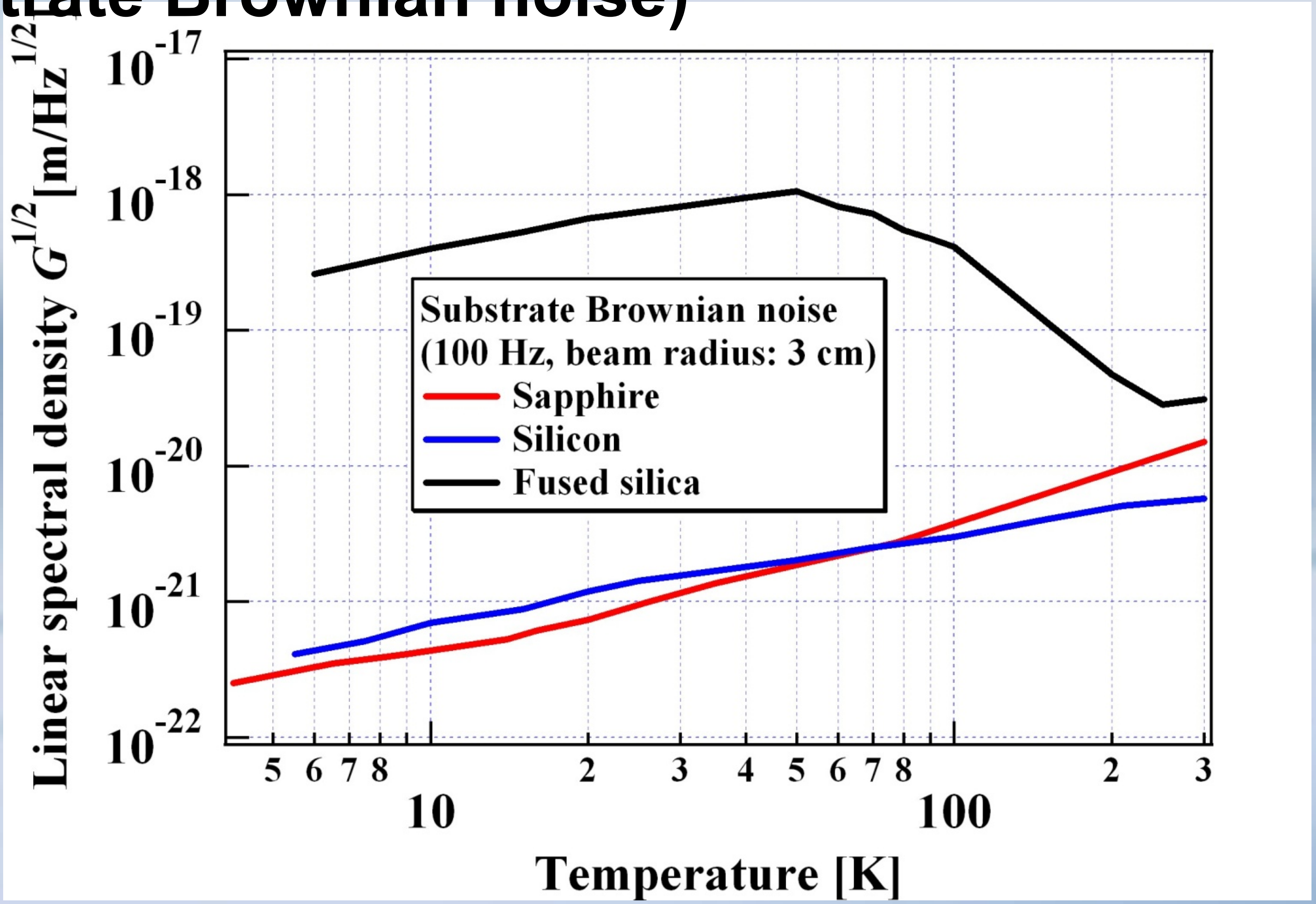
2. Thermal noise

Thermal noise by structure damping in substrate (Substrate Brownian noise)

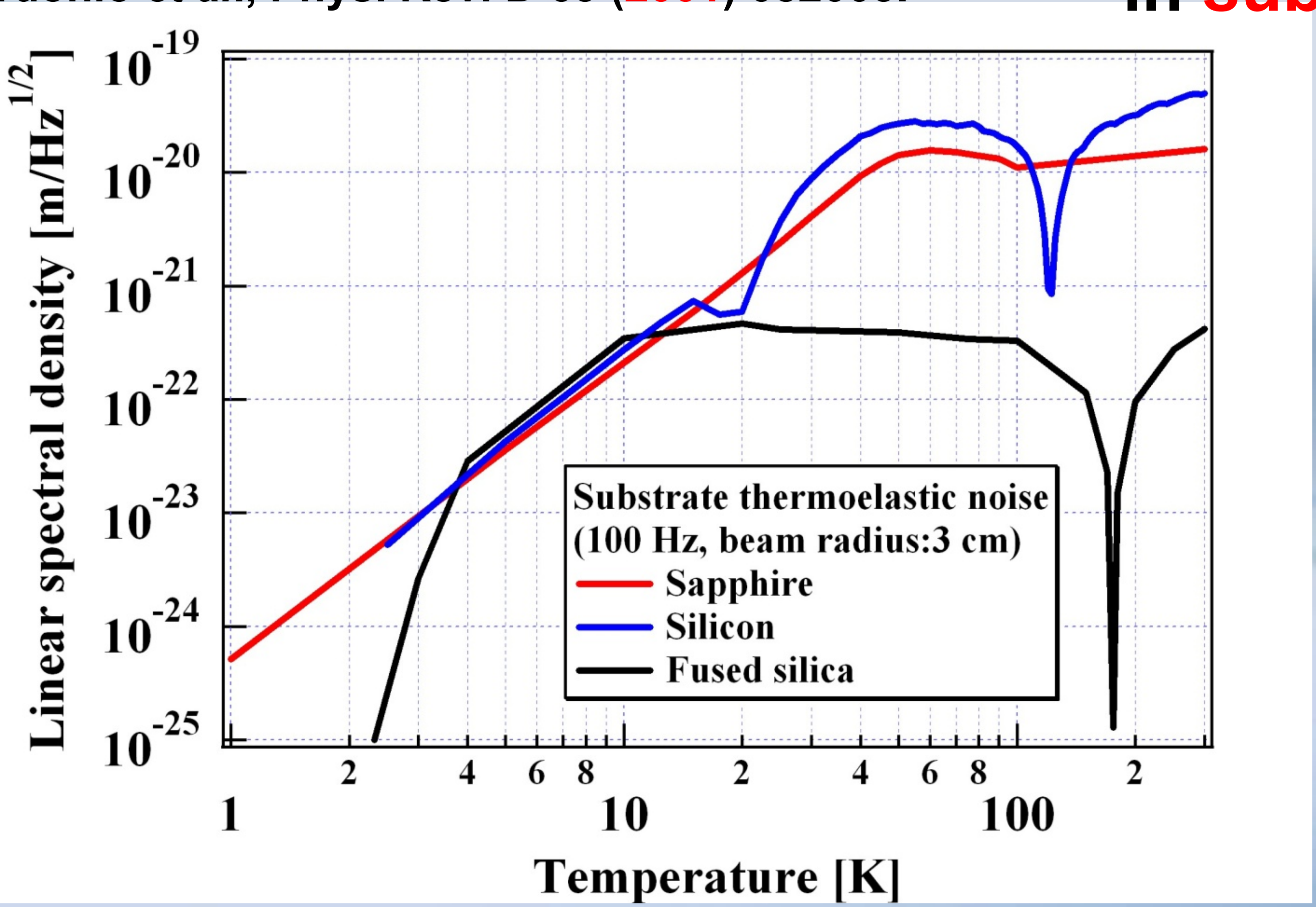


Kenji Numata and Kazuhiro Yamamoto,"Chapter 8. Cryogenics", in "Optical Coatings and Thermal Noise in Precision Measurement" Cambridge University Press (2012).

2. Thermal noise

Thermal noise by thermoelastic damping in substrate

M. Cerdonio *et al*., Phys. Rev. D 63 (2001) 082003.



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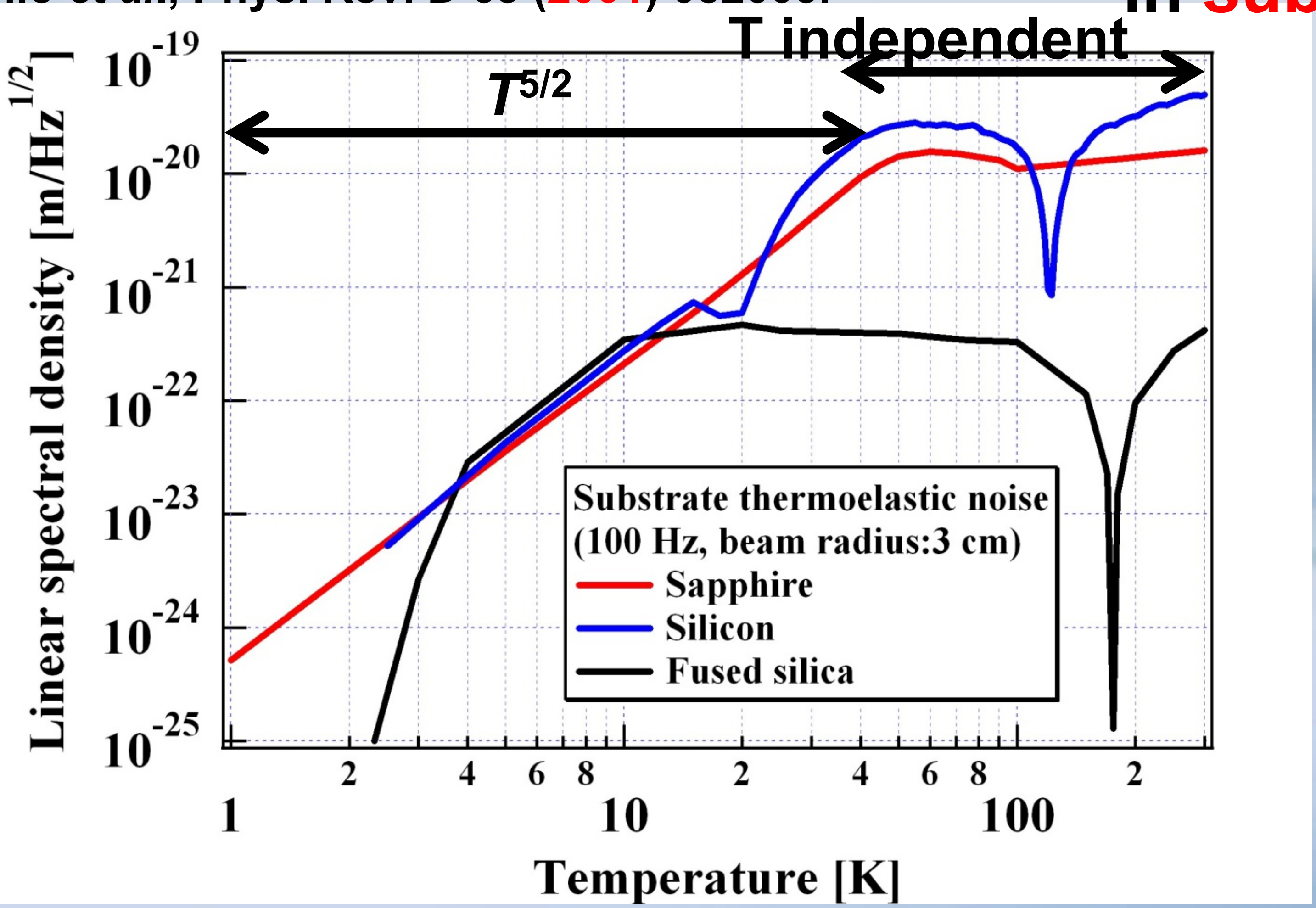

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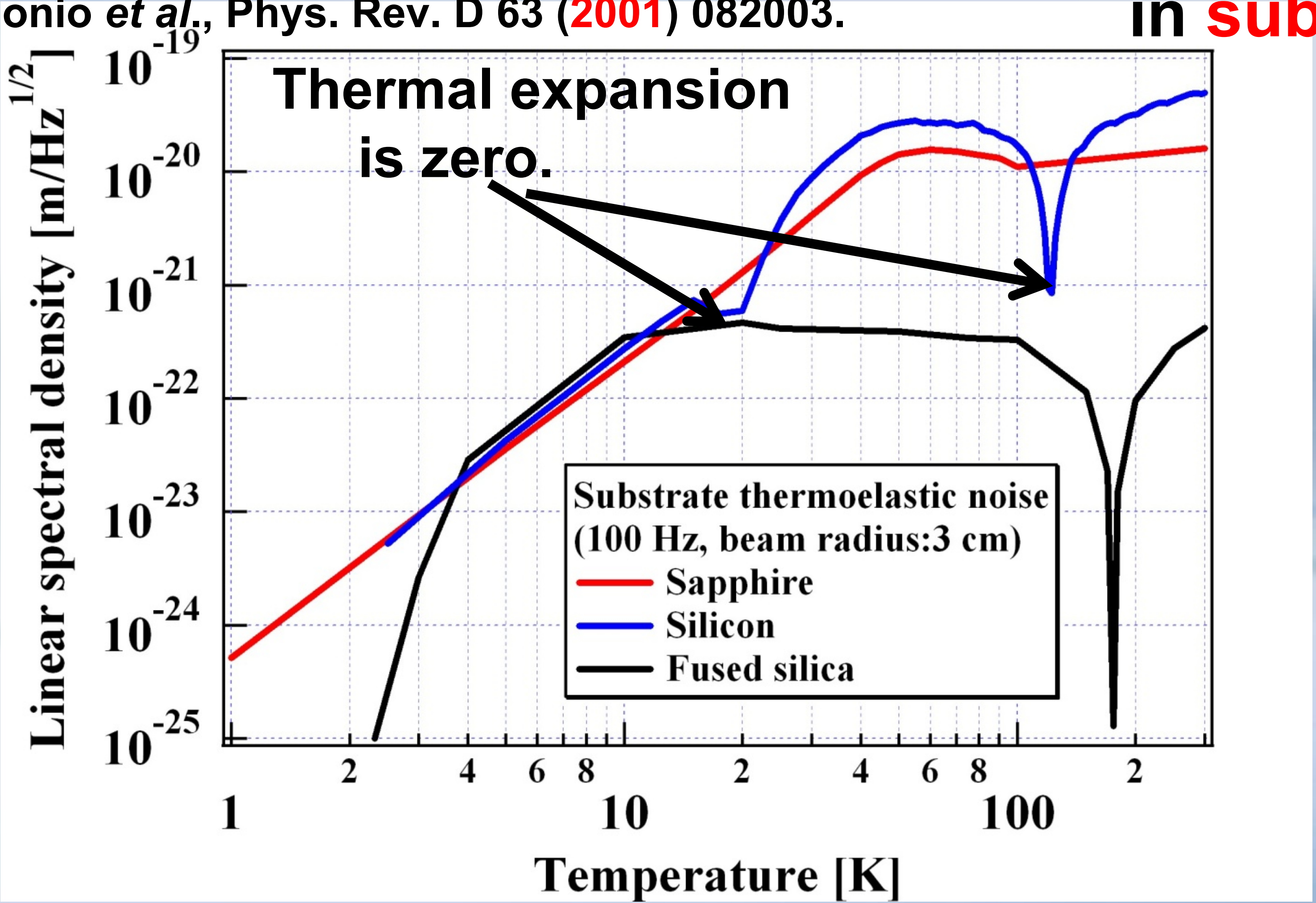


Kenji Numata and Kazuhiro Yamamoto,"Chapter 8. Cryogenics", in "Optical Coatings and Thermal Noise in Precision Measurement" Cambridge University Press (2012).

2. Thermal noise

Structure damping in coating

Y. Levin, Phys. Rev. D 57 (1998) 659.

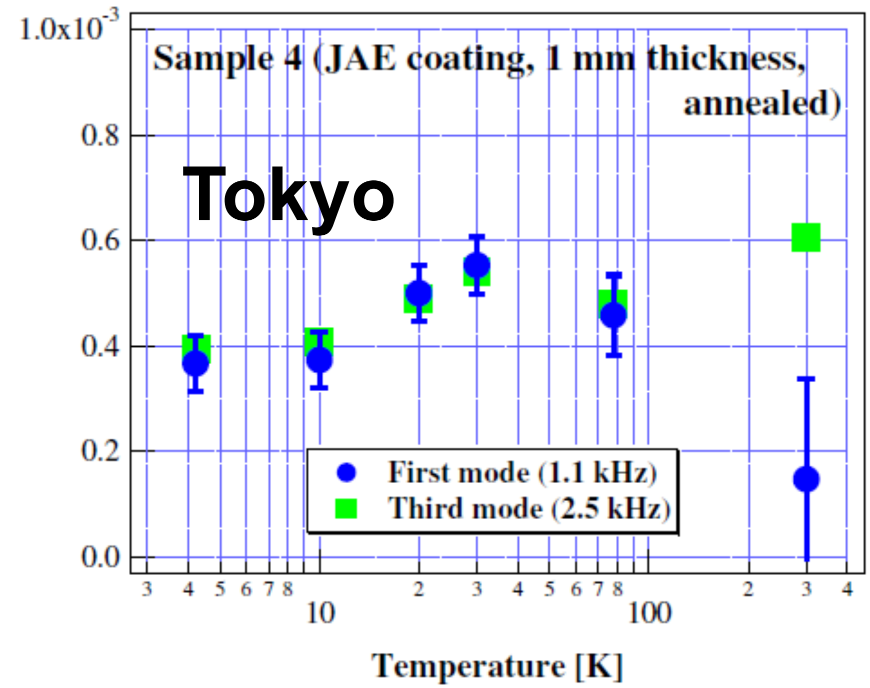
Coating has large contribution to thermal noise than we expected !

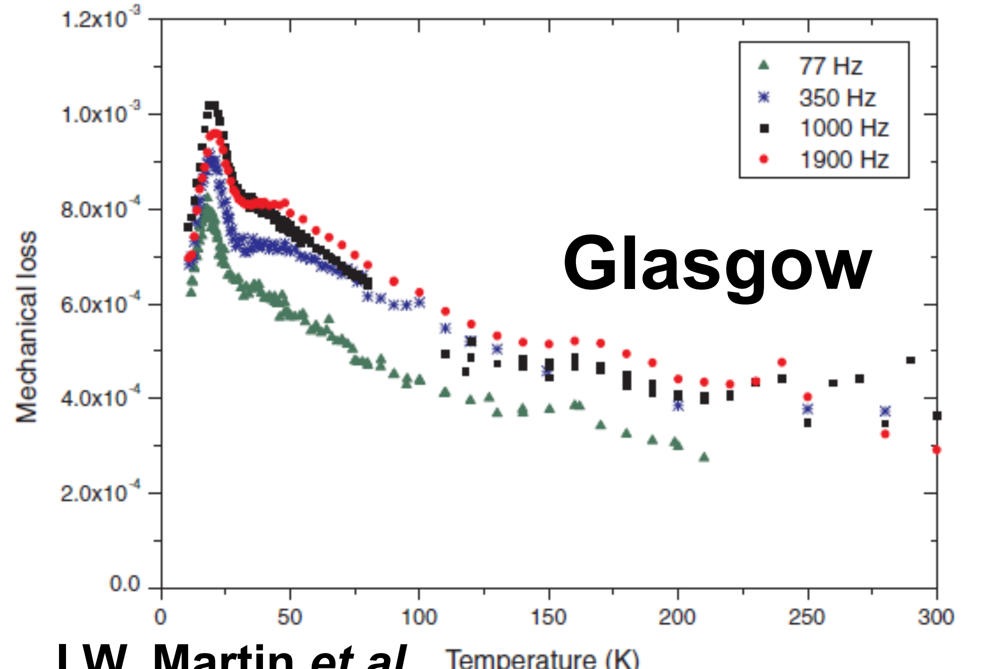
This noise is proportional to $\phi^{1/2}$.

ϕ is loss strength (it is inverse number of Q-values).

2. Thermal noise

Structure damping in coating (Ta_2O_5/SiO_2)





K. Yamamoto *et al*.,
Physical Review D 74 (2006) 022002.

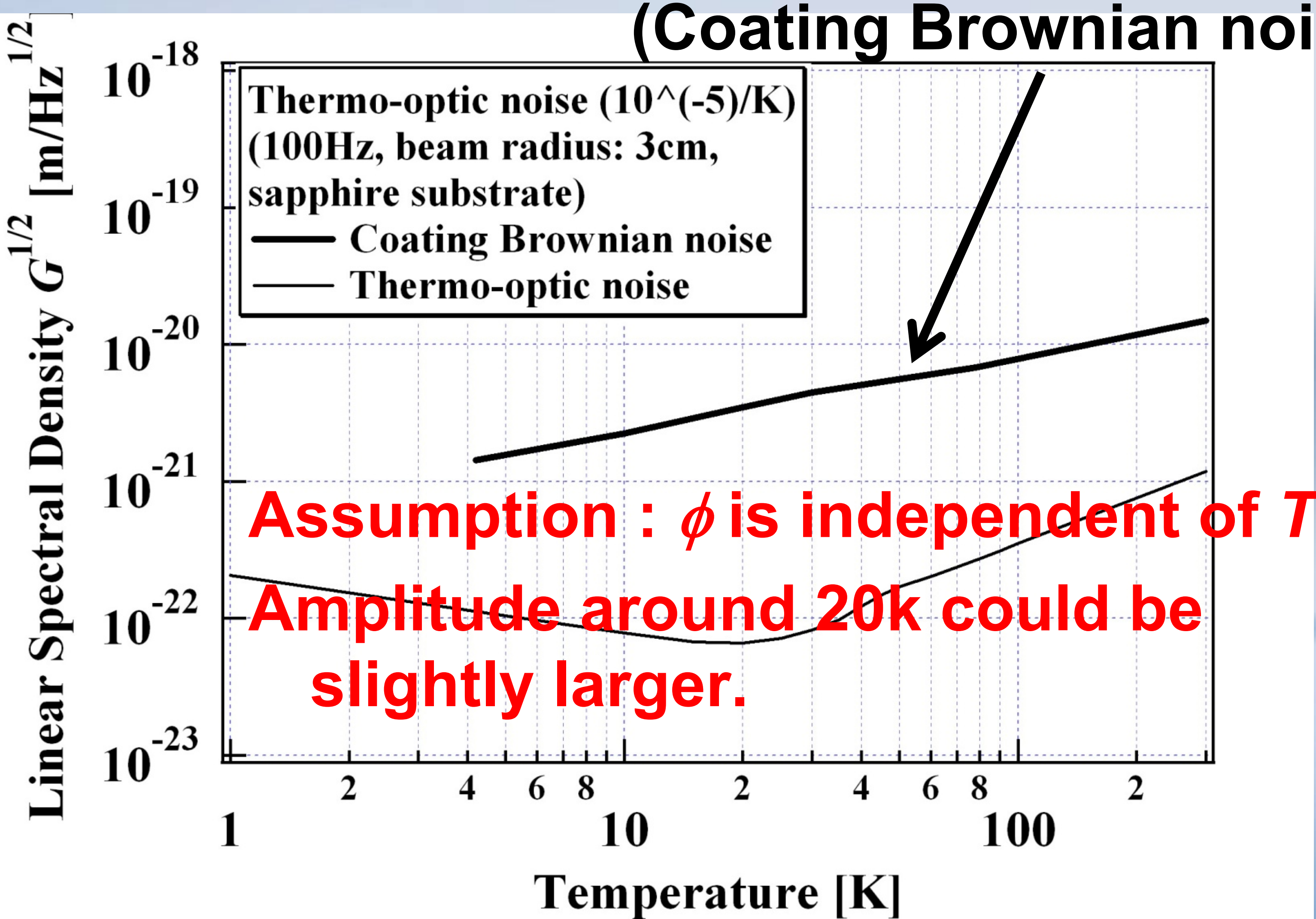
I.W. Martin *et al*.,
Classical and Quantum Gravity
27 (2010) 225020.
(Annealing could suppress peak)

Many experiments show peak around 20K.

2. Thermal noise

Thermal noise by structure damping in coating

(Coating Brownian noise)



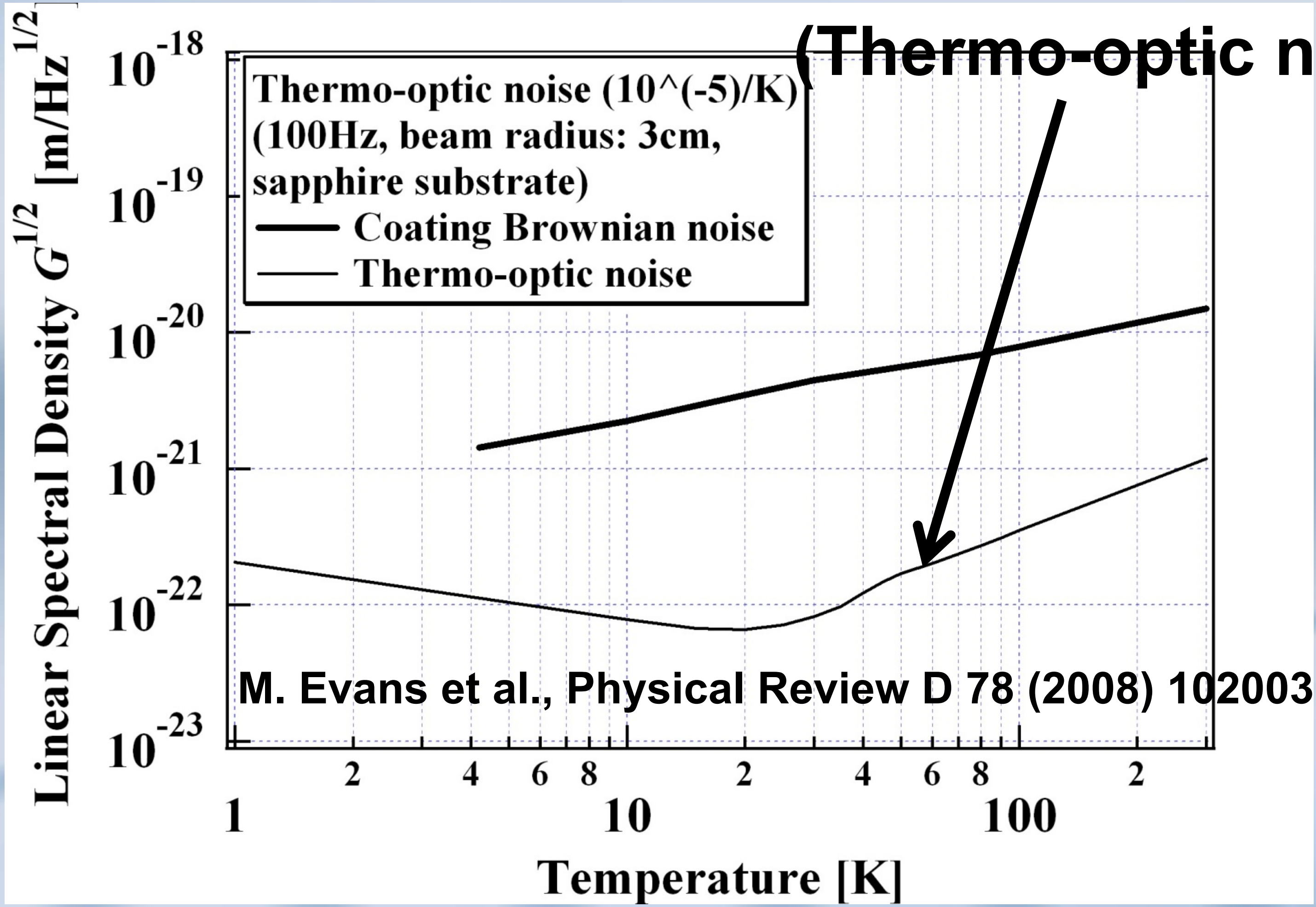
Assumption : ϕ is independent of *T*.

Amplitude around 20k could be slightly larger.

2. Thermal noise

Thermal noise by thermoelastic damping in coating

(Thermo-optic noise)



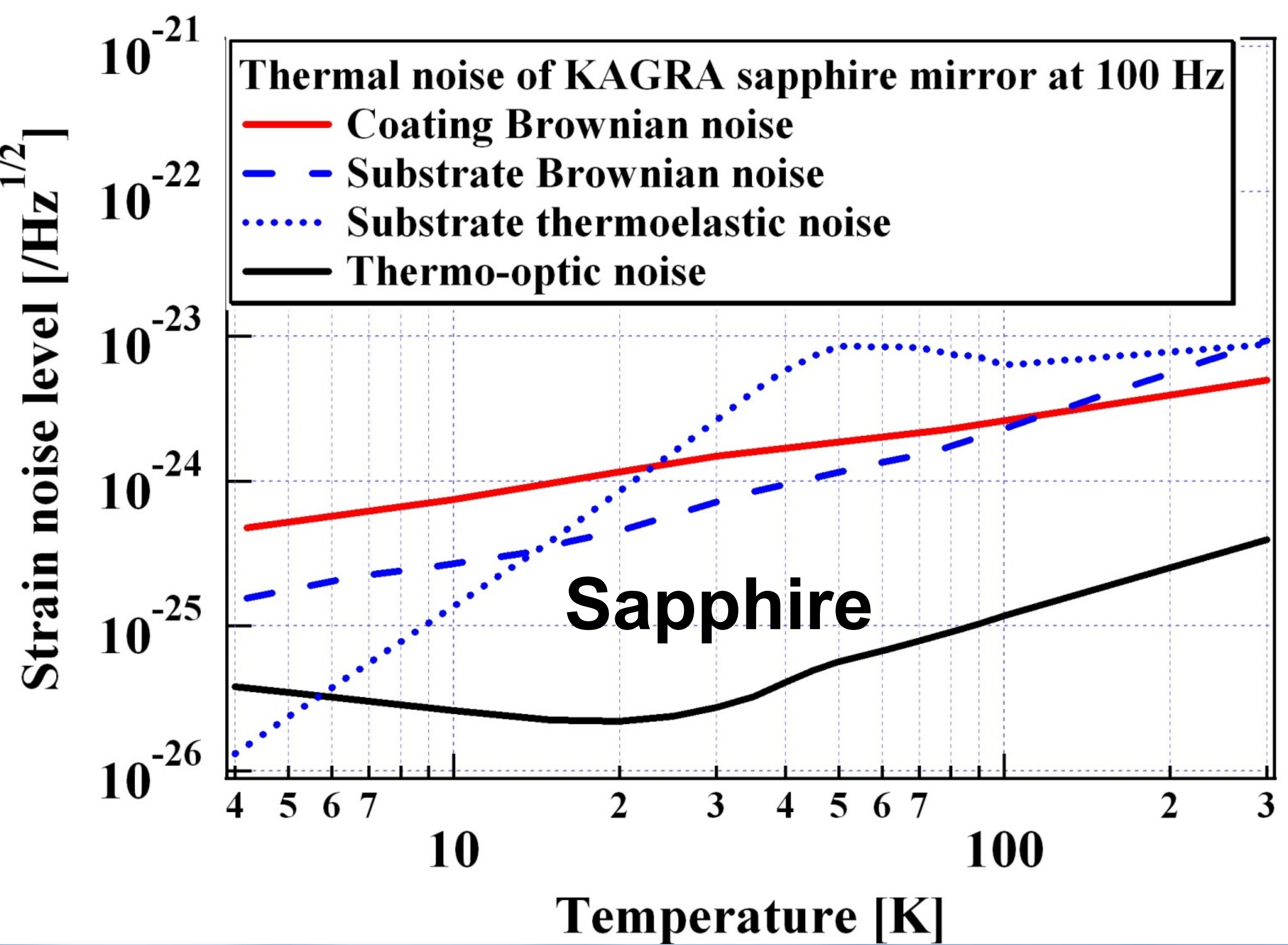
Thermo-optic noise is much smaller than coating Brownian noise.

2. Thermal noise

Summary : Sapphire mirror
In principle, lower temperature is better.

> 50K
Constant

<20K
Enough small



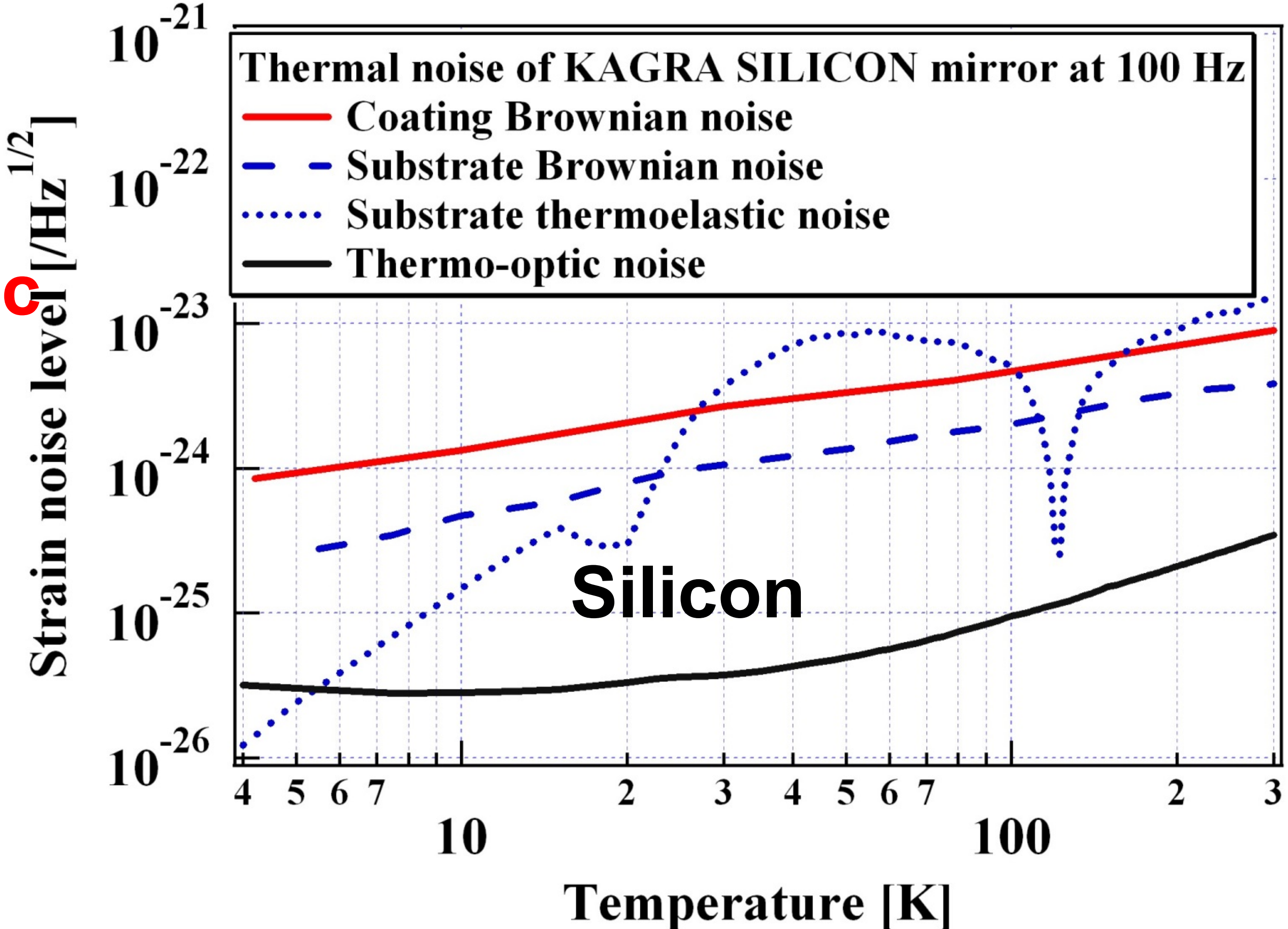
2. Thermal noise

Summary : Silicon mirror

In principle, lower temperature is better.

120K Thermoelastic noise vanishes.

Temperature control is necessary.



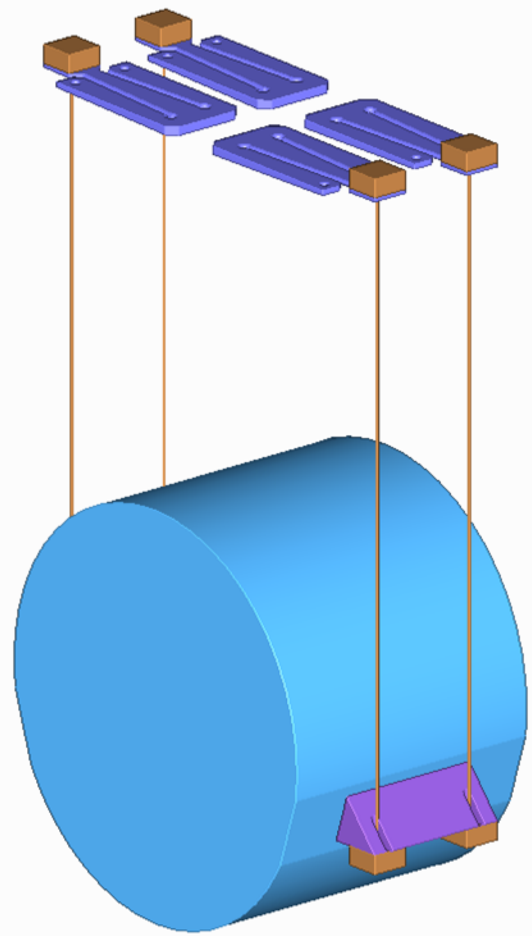
2. Thermal noise

Mirror substrate and operation temperature

Sapphire, 20 K : CLIO, KAGRA

Silicon, 10 K : Einstein Telescope

Silicon, 120K : Voyager
Cosmic Explorer

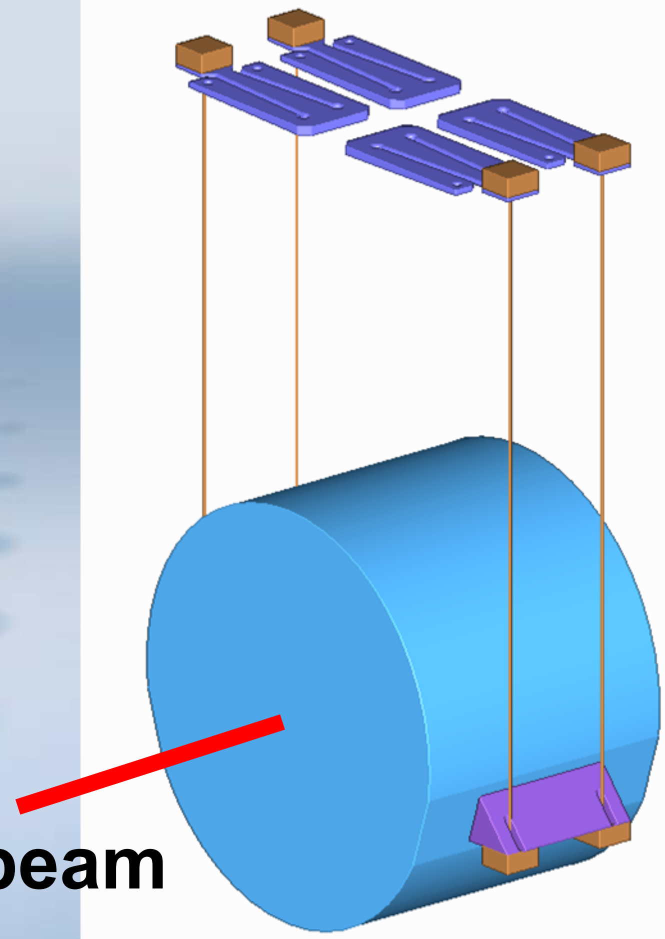


2. Thermal noise

Mirror substrate and operation temperature

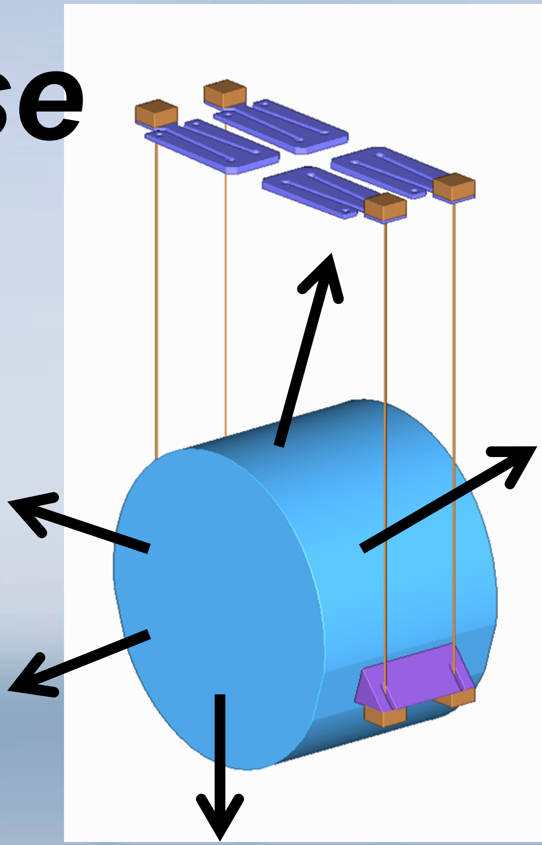
Heat absorption in mirror is an serious issue. How can we avoid that mirror could be hot ?

Typical heat absorption in mirror
1W – 10 W



Laser beam

2. Thermal noise

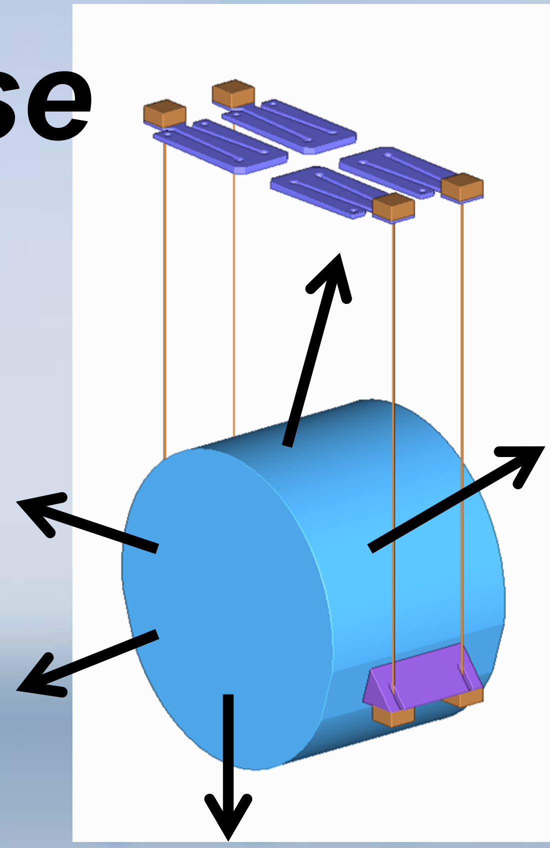


120K operation (Silicon)

Heat absorbed in mirror : **Several W**

Radiation from mirror is effective.
When mirror is surrounded
by **cold wall** (radiation shield),
radiation from mirror carries much heat ;
13 W/m^2 at most (Black body radiation).
Surface of mirror is 0.3 m^2 at least.

2. Thermal noise

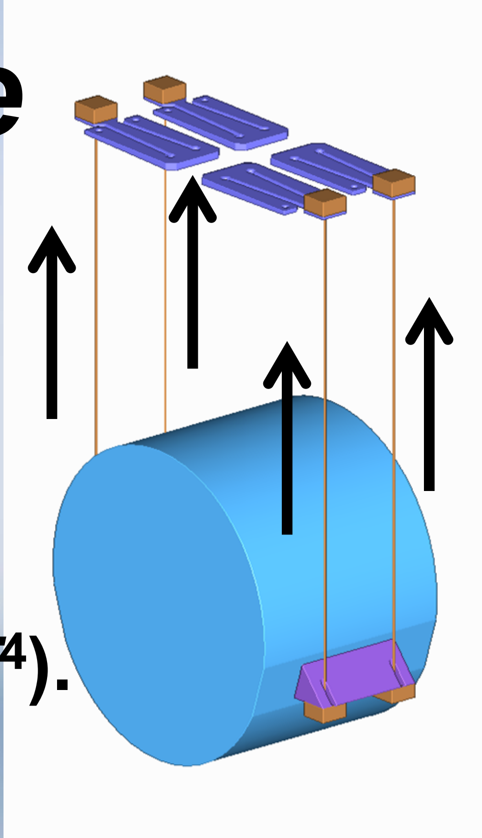


120K operation (Silicon)

Black coating on mirror is necessary.
It should have small mechanical dissipation and so on.

Fiber to suspend mirror can be as thin as possible (Fiber must support weight of mirror).
Typical diameter is 0.5 mm.

2. Thermal noise



Below 20K operation (Sapphire, Silicon)

Heat absorbed in mirror : about 1 W

Heat extraction : Radiation is useless (T^4).
Conduction in fibers
Sapphire or silicon has extremely high conductivity (5000 W/m/K).

But, thicker fiber for heat conduction (1.6 mm in diameter, KAGRA) is necessary.
When heat transfer is not necessary, 0.5 mm in diameter.

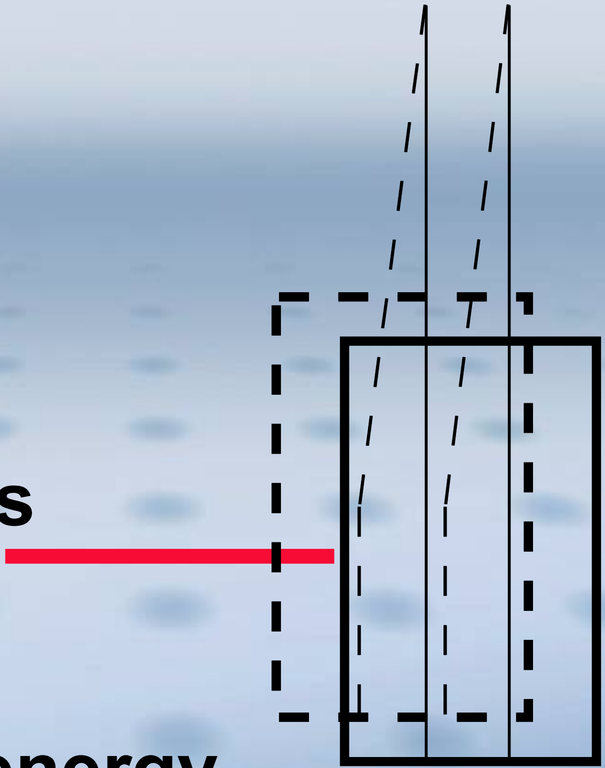
2. Thermal noise

What is an issue of thicker fiber ?

Larger pemdulum thermal noise

Energy of pendulum mode
= gravitational potential energy
+ fiber elastic energy.

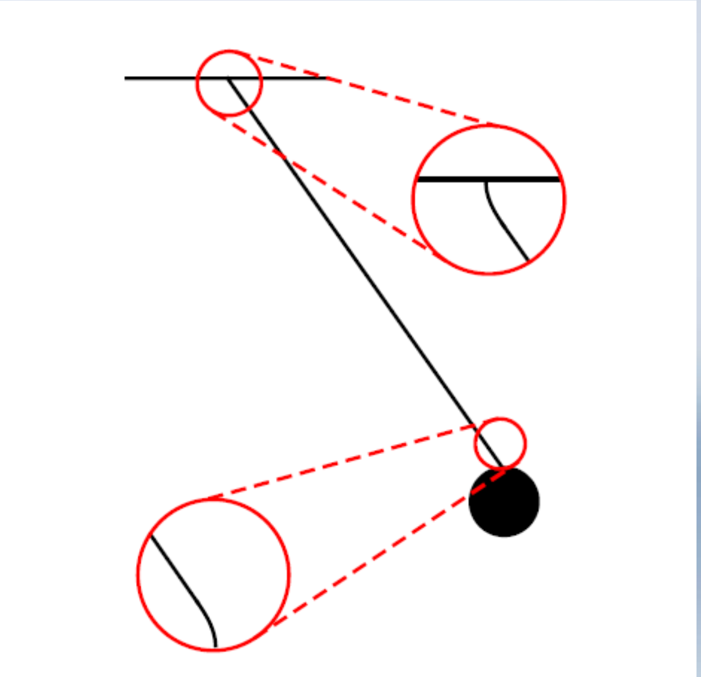
Gravitational potential energy has no loss. Elastic energy has loss.



Thicker fibers has larger elastic energy, loss, and thermal noise.

2. Thermal noise

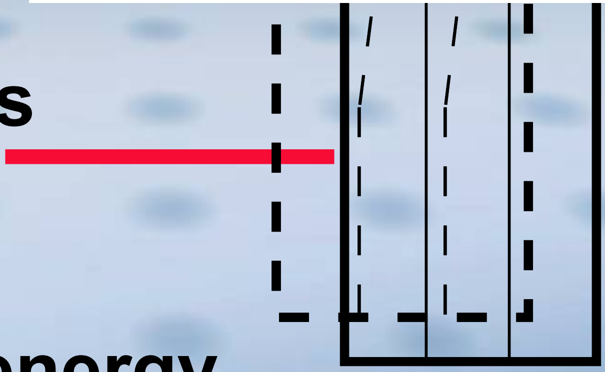
What is an issue of **thicker fiber** ?



Larger suspension thermal noise

Energy of pendulum mode
= gravitational potential energy
+ fiber elastic energy.

Gravitational potential energy has no loss. Elastic energy has loss.



Thicker fibers has larger elastic energy, loss, and thermal noise.

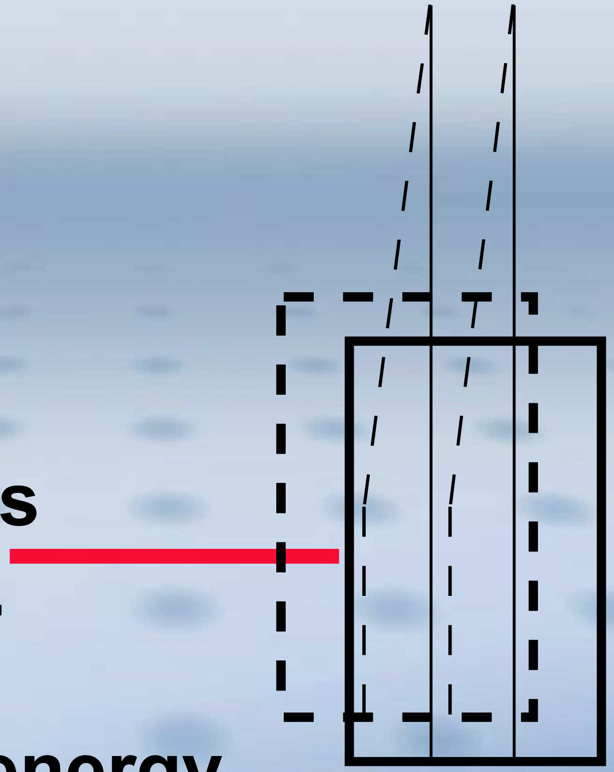
2. Thermal noise

What is an issue of **thicker fiber** ?

Larger pemdulum thermal noise

Energy of **pendulum mode**
= gravitational potential energy
+ fiber elastic energy.

Gravitational potential energy has **no loss**. **Elastic energy** has **loss**.



Thicker fibers has **larger** elastic energy, loss, and **thermal noise**.

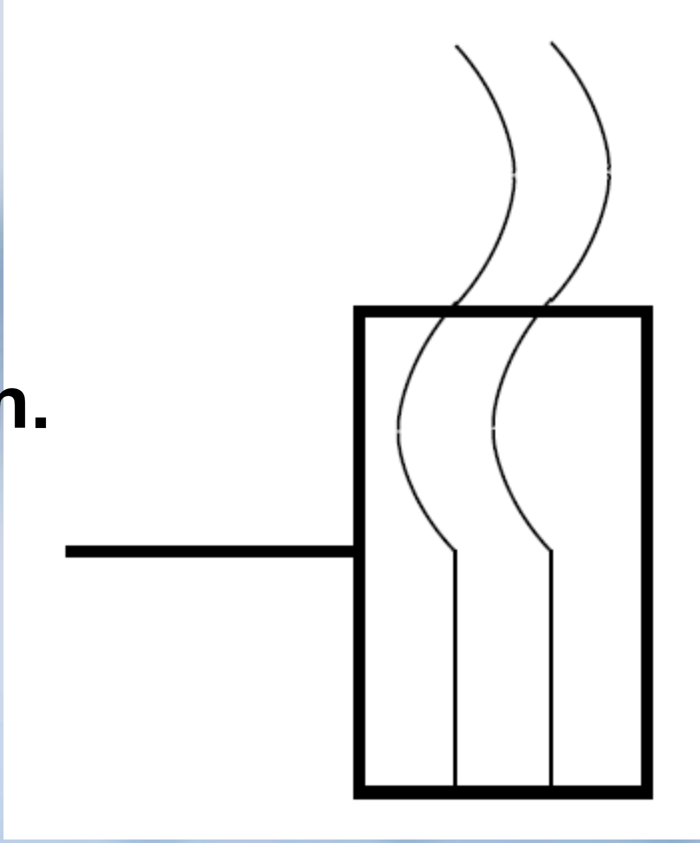
2. Thermal noise

What is an issue of thicker fiber ?

Thermal noise of violin mode

Violin mode : Back action of fiber.

Thicker fiber has large back action.
Mode frequency is lower.



2. Thermal noise

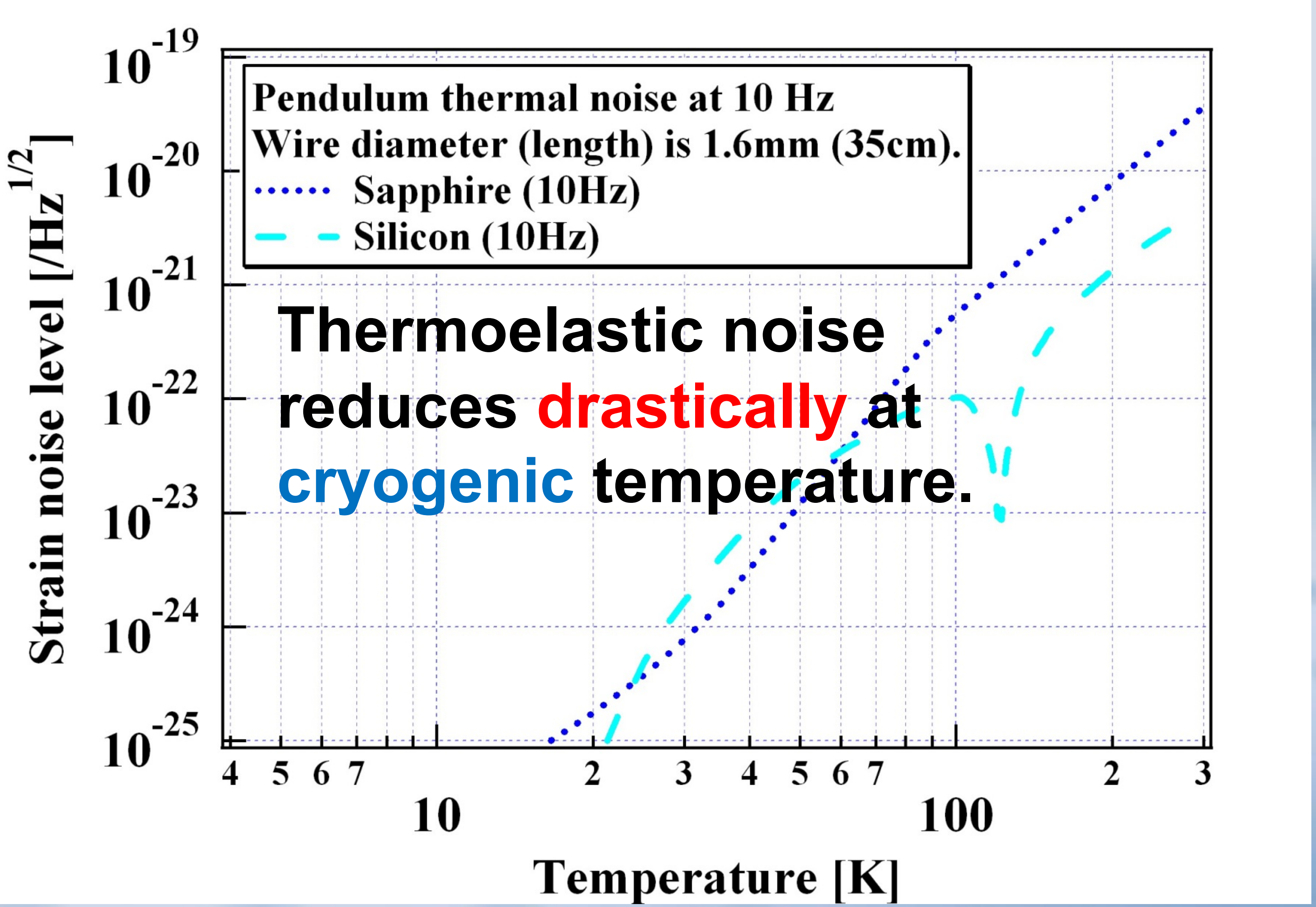
Mechanical dissipation in fibers generates suspension thermal noise.

Two kinds of loss : Structure, Thermoelastic

Note : Both of them in fiber is different from those in 3 dimensional bulk.

2. Thermal noise

Pendulum thermal noise (Thermoelastic damping)

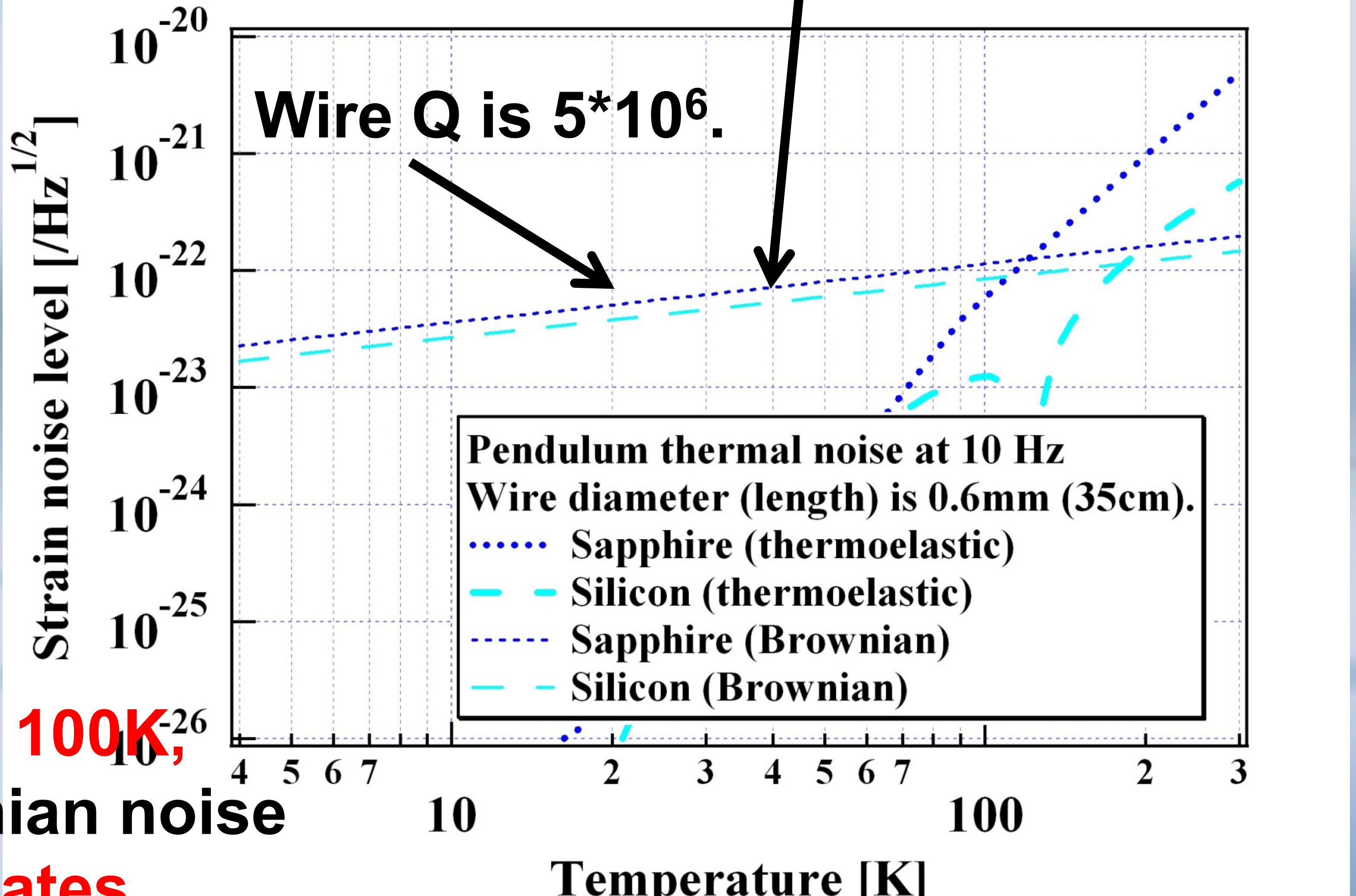


Thermoelastic noise reduces **drastically** at **cryogenic** temperature.

2. Thermal noise

Pendulum thermal noise (Structure damping)

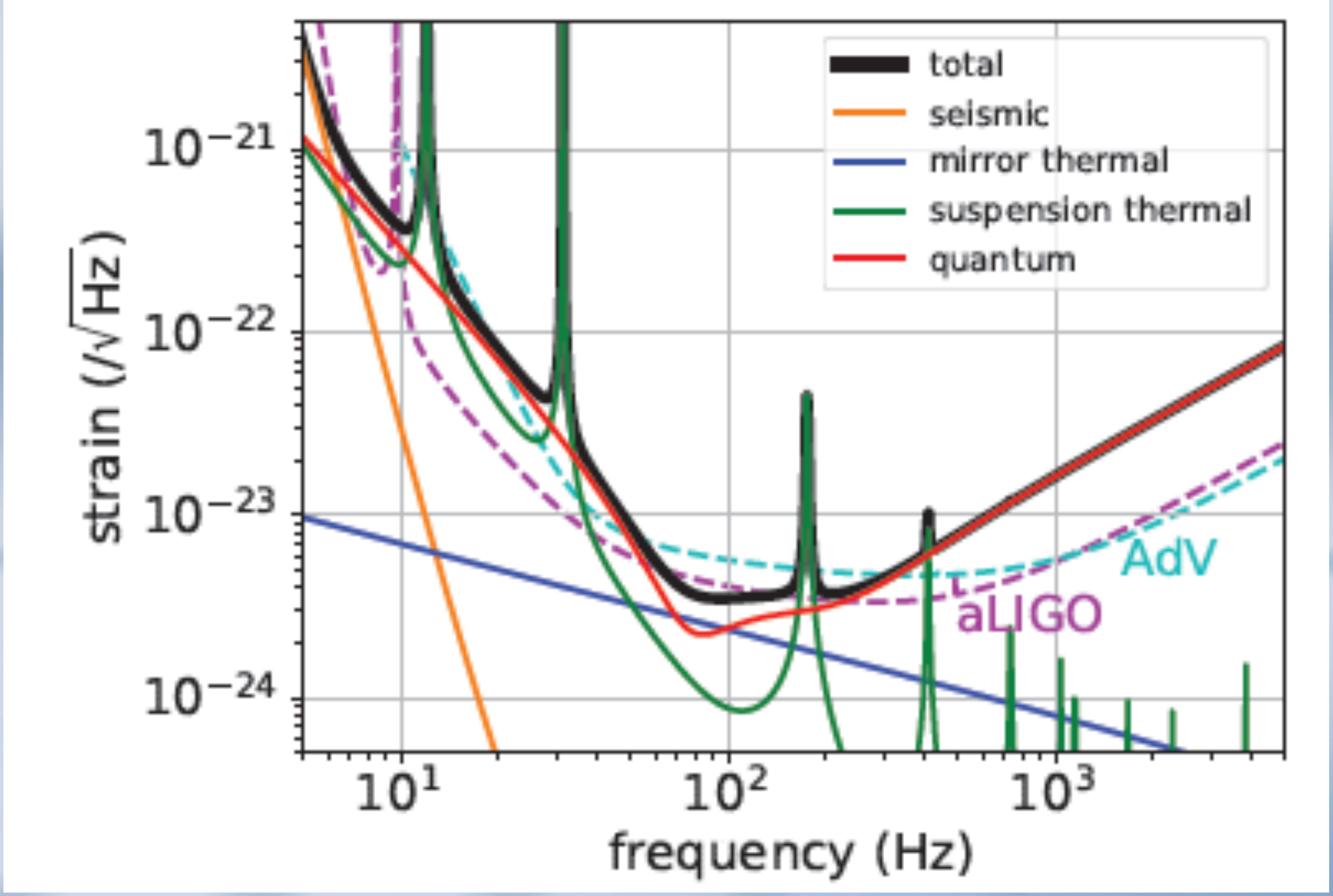
Brownian noise



Below 100K, Brownian noise dominates.

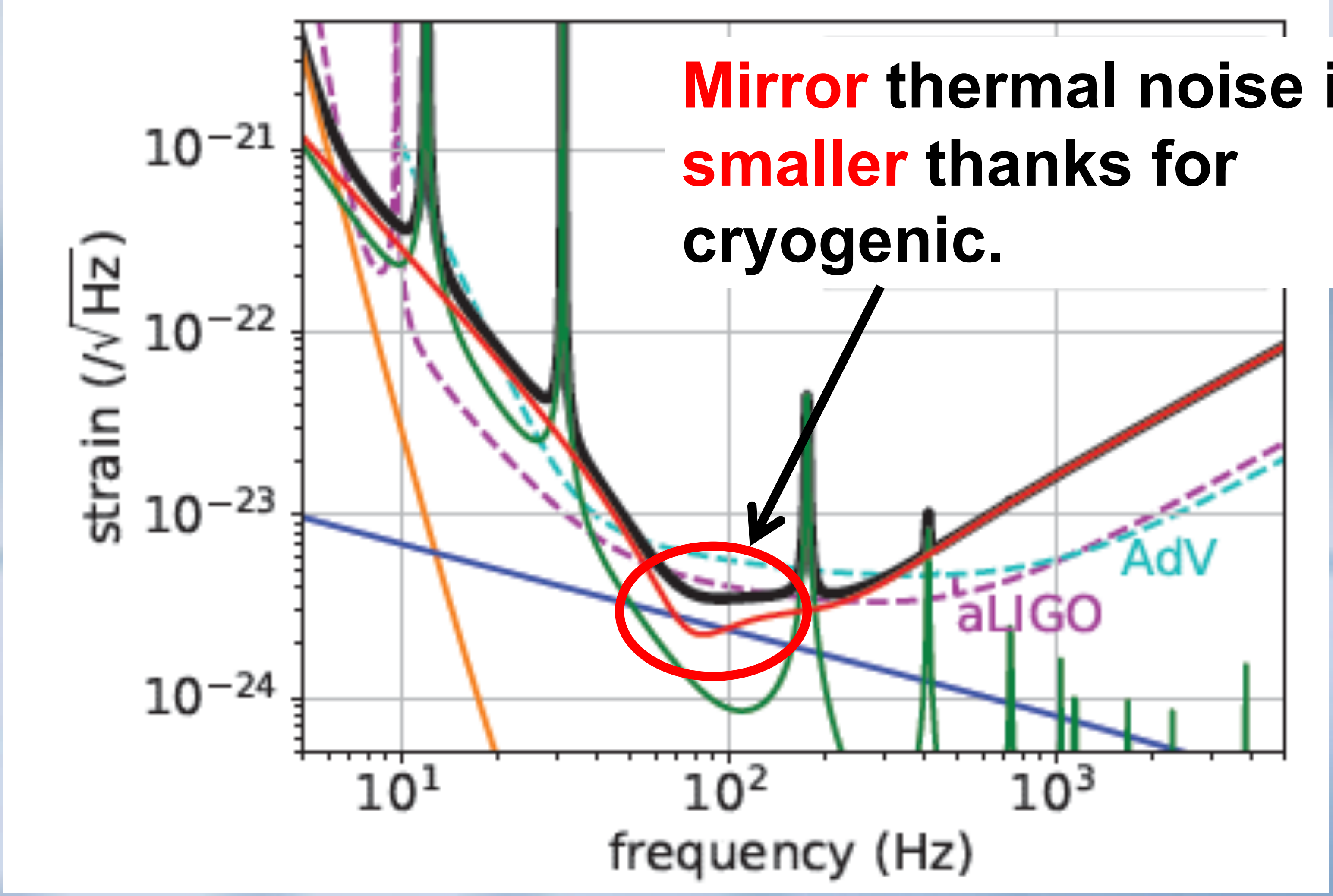
2. Thermal noise

Comparison of KAGRA (Sapphire, 20K) with room temperature interferometer



2. Thermal noise

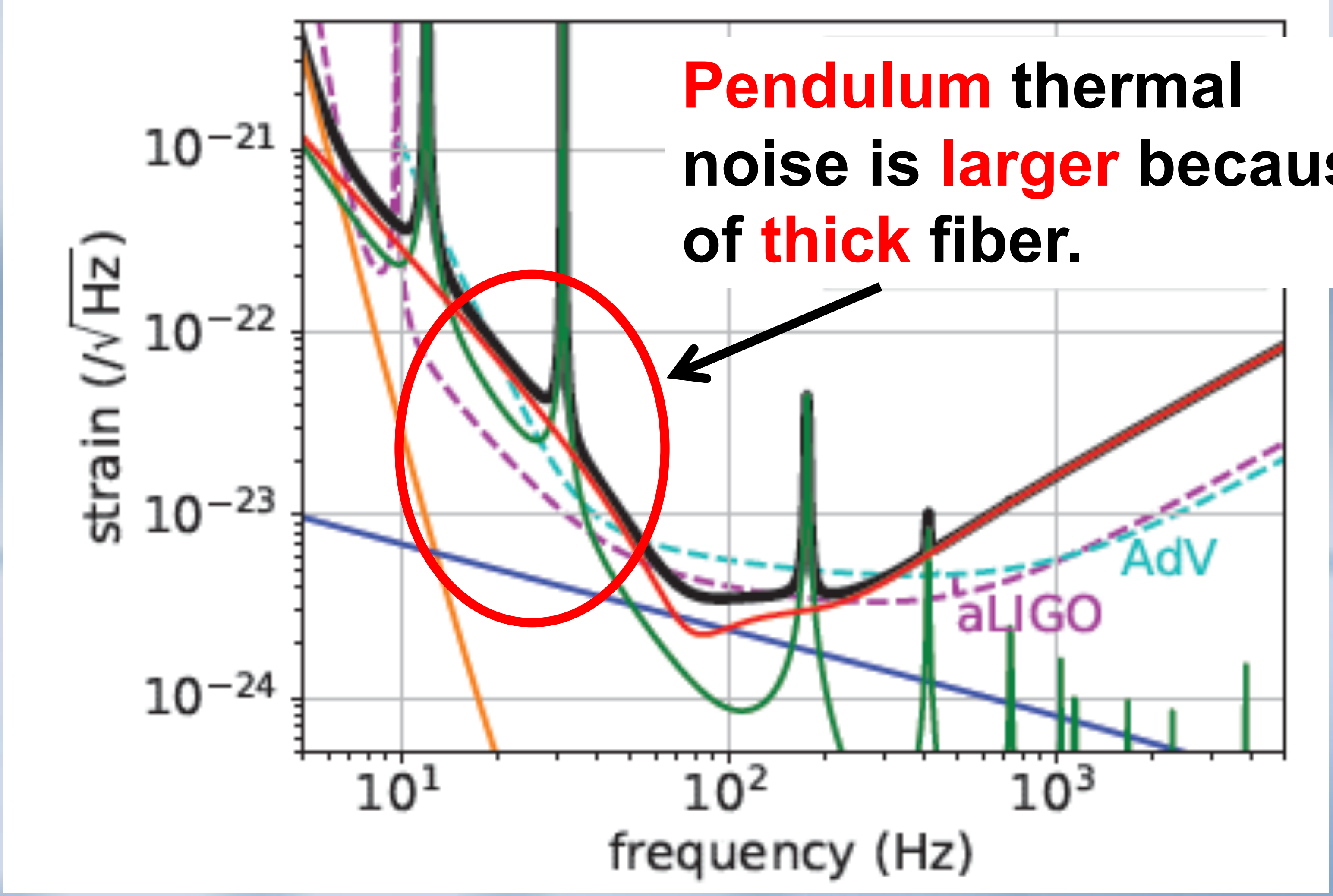
Comparison of KAGRA (Sapphire, 20K) with room temperature interferometer



Mirror thermal noise is smaller thanks for cryogenic.

2. Thermal noise

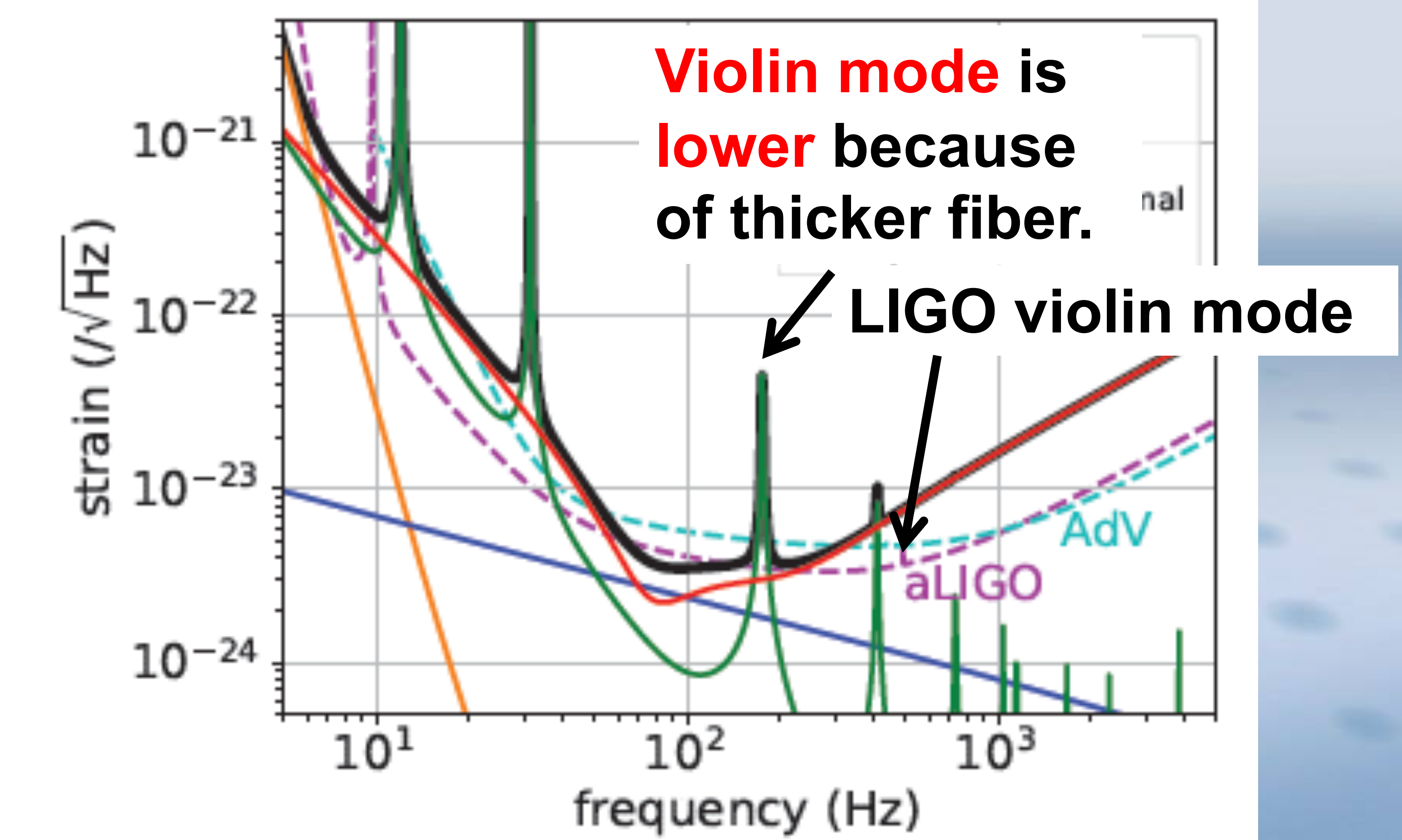
Comparison of KAGRA (Sapphire, 20K) with room temperature interferometer



Pendulum thermal noise is **larger** because of **thick** fiber.

2. Thermal noise

Comparison of KAGRA (Sapphire, 20K) with room temperature interferometer



2. Thermal noise

Sapphire, Silicon, 20K

Mirror thermal noise is small.

Suspension (pendulum and violin mode)

thermal noise is an issue

(because of thick fiber or heat transmission).

Solution

(1) Lower frequency interferometer

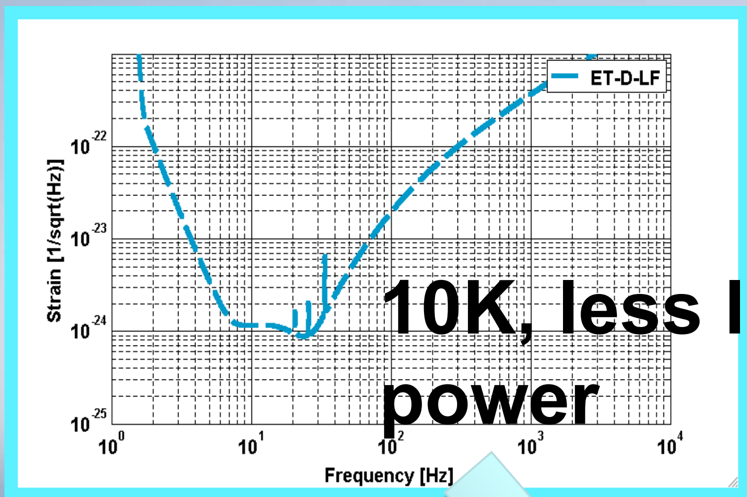
with lower laser power (Einstein Telescope)

(2) Small heat absorption mirror

Large thermal conductivity fibers

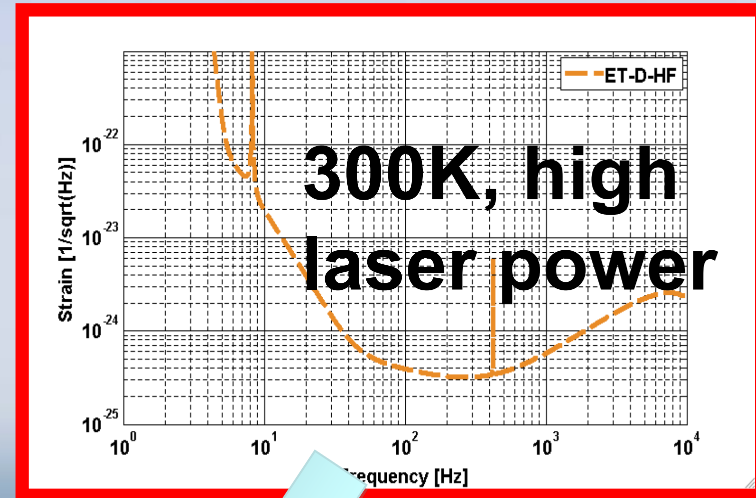
KAGRA

2. Thermal noise



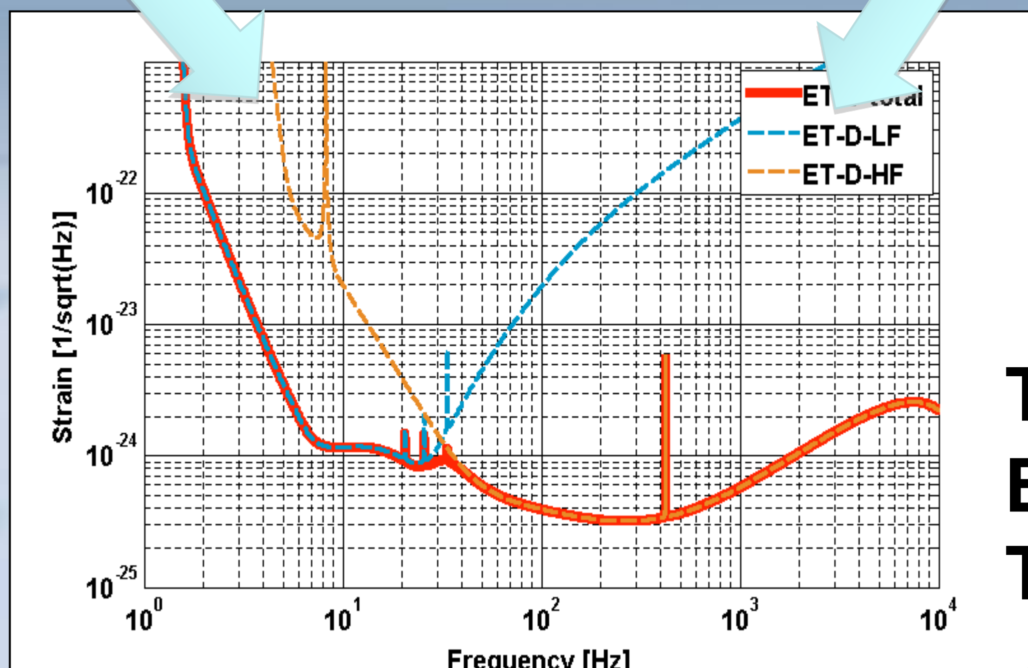
10K, less laser power

ET-D-LF



300K, high laser power

ET-D-HF



Total of Einstein Telescope

2. Thermal noise

Sapphire, Silicon, 20K

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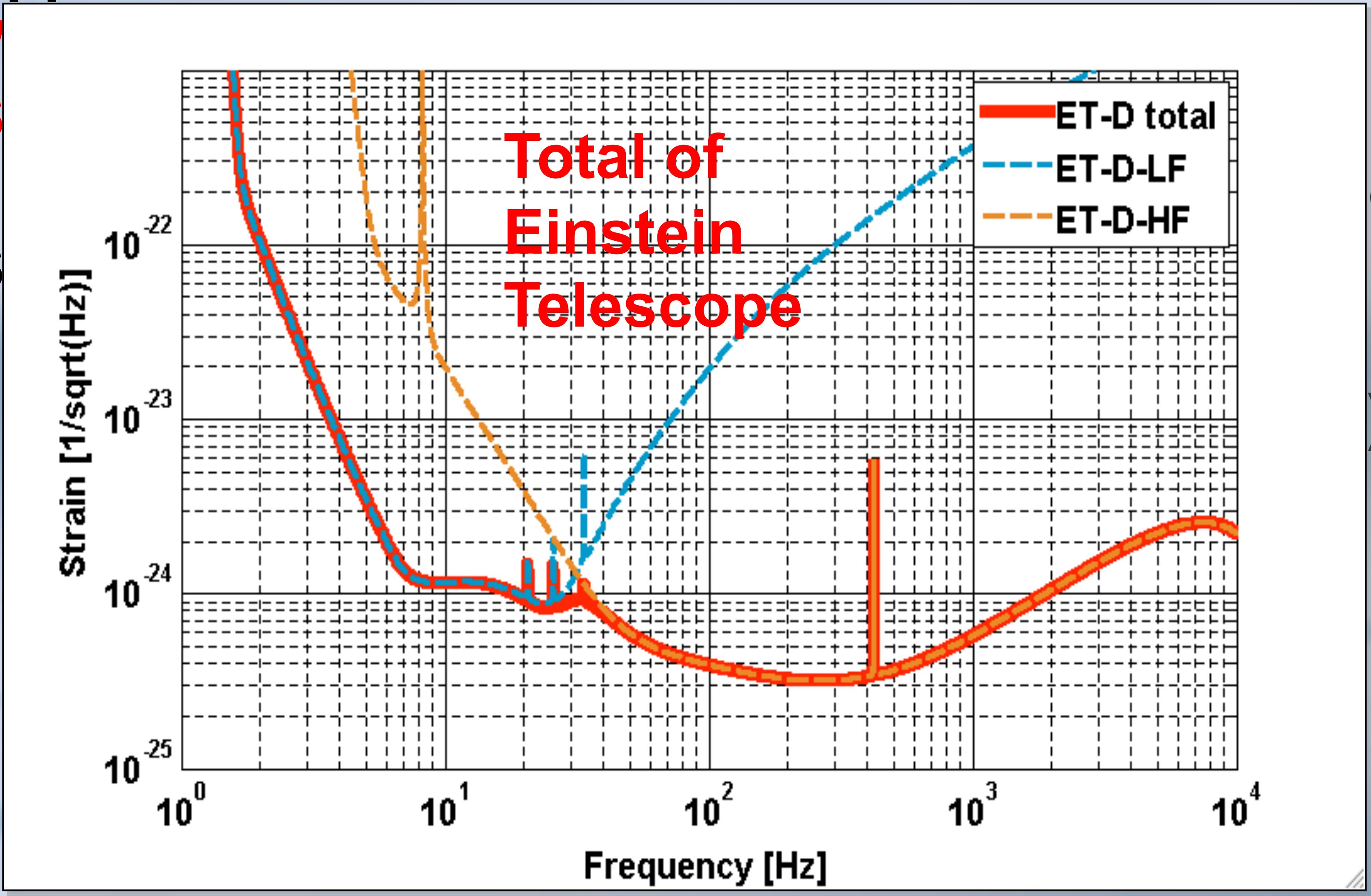
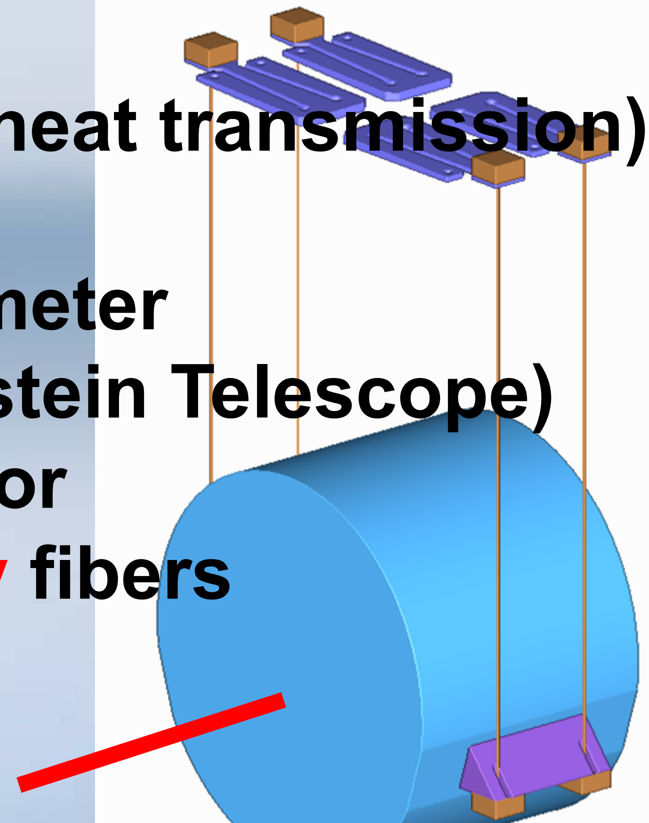


2. Thermal noise

Sapphire, Silicon, 20K

- **Mirror thermal noise is small.**
- **Suspension (pendulum and violin mode) thermal noise is an issue (because of thick fiber or heat transmission).**
- **Solution**
  - **(a) Lower frequency interferometer with lower laser power (Einstein Telescope)**
  - **(b) Small heat absorption mirror**
    Large thermal conductivity fibers



2. Thermal noise

(a) Low heat absorption in mirror

If heat absorption in mirror (not only substrate but also coating) is 10 - 30 times smaller, the fiber can be as thin as possible (More thinner fiber can not support mirror).

Substrate : Small absorption (a few ppm/cm) in small sample was reported. So not impossible …

Coating : It is exactly challenge …

2. Thermal noise

(b) Higher thermal conductivity

Size effect : Thermal conductivity is proportional to fiber diameter .

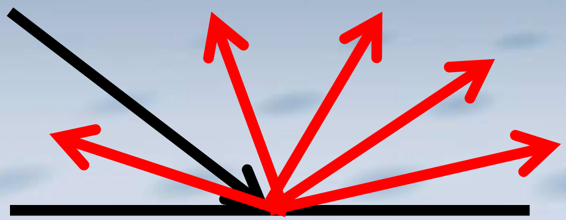
Phonon mean free path is comparable with diameter.
It sounds like upper limit of thermal conductivity.
But, ..

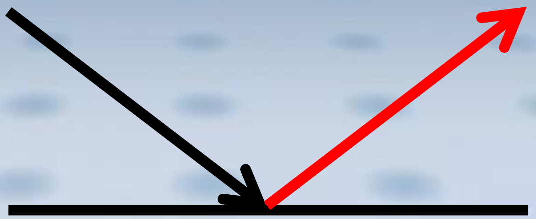
2. Thermal noise

(b) Higher thermal conductivity

It is assumed that phonon is duffed on fiber surface as like molecules in vacuum duct.

But phonon reflection is specular as like light, thermal conductivity could be larger.





Thermal conductivity (limited by size effect) of silicon is larger when fiber surface is polished .

Phys. Rev. 186, 801 (1969)

3. Other merits

Other merits of cooled mirror ?

(1) Thermal lens

(2) Parametric instability

3. Other merits

Thermal lens : <u>Light absorption in mirror</u>

Temperature gradient

Temperature dependent of refractive index

Wave front distortion

Worse sensitivity

3. Other merits

Thermal lens : Light absorption in mirror

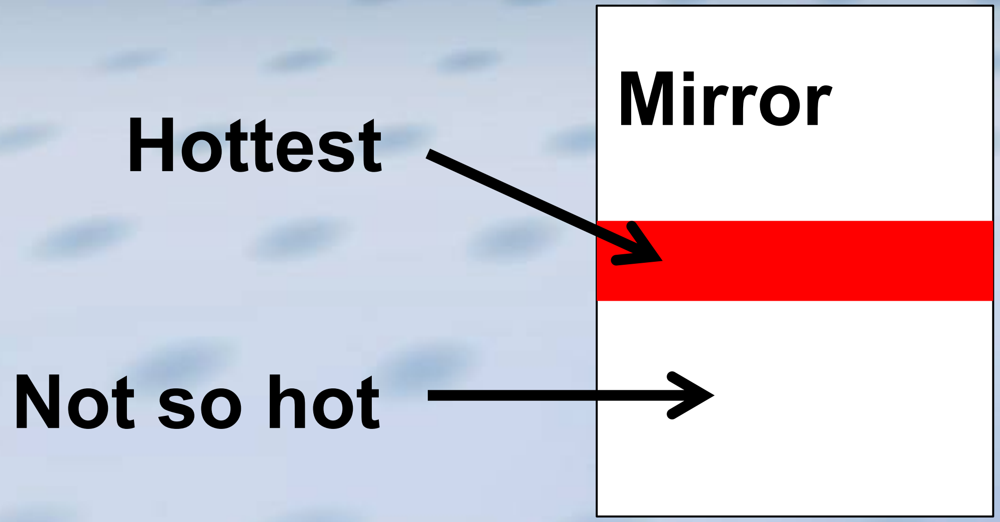
<u>Temperature gradient</u>

Temperature dependent

of refractive index

Wave front distortion

Worse sensitivity



3. Other merits

Thermal lens : Light absorption in mirror

Temperature gradient

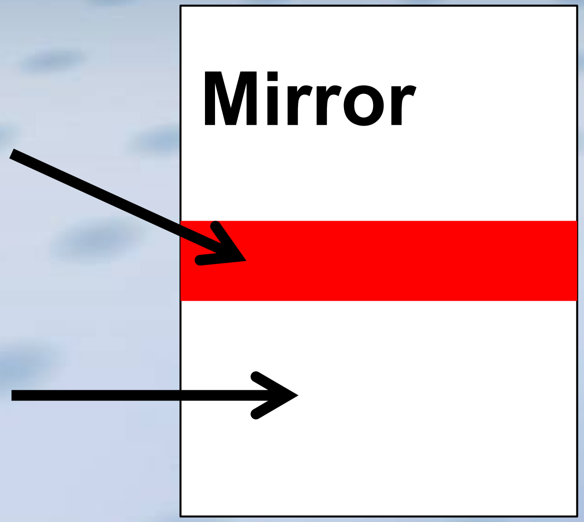
Temperature dependent of refractive index

Wave front distortion

Worse sensitivity

Higher or lower refractive index

Refractive index does not change.



Some kind of imperfect lens !

3. Other merits

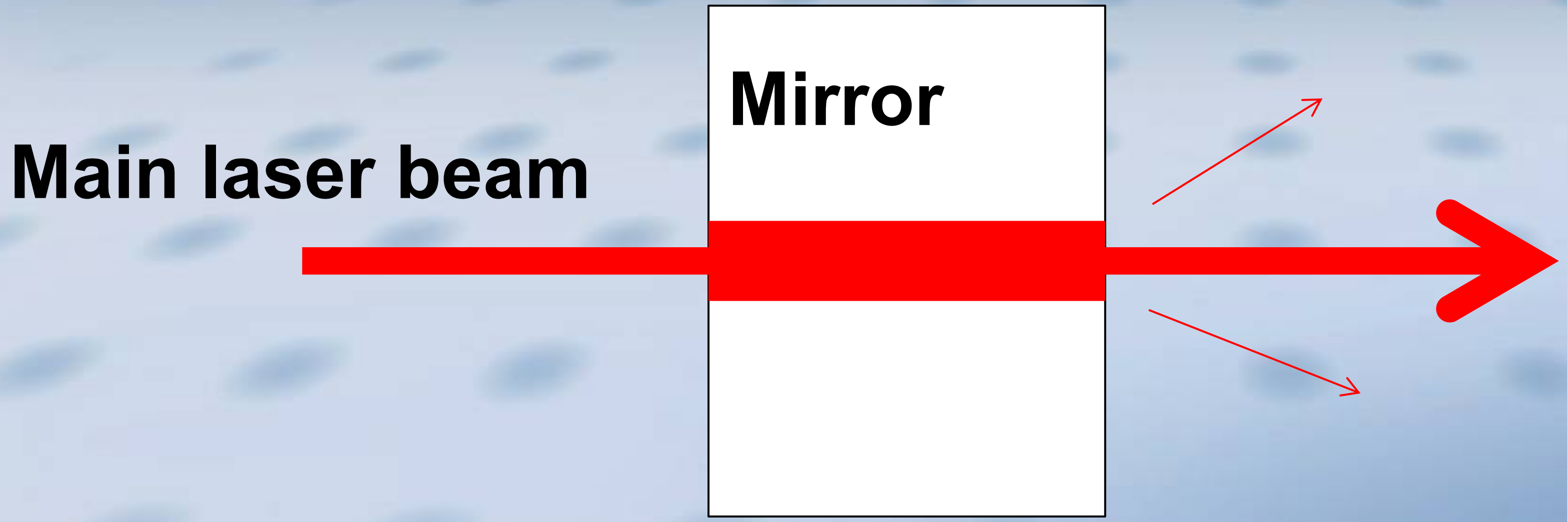
Thermal lens : Light absorption in mirror

Temperature gradient

Temperature dependent of refractive index

<u>Wave front distortion</u>

<u>Worse sensitivity</u>



3. Other merits

Thermal lens is a serious problem of room temperature interferometers.

Advanced LIGO and Virgo : System to compensate thermal lens (compensation plate and ring heater) is necessary.

G.M. Harry (for LSC), Classical and Quantum Gravity 27 (2010) 084006.

3. Other merits

KAGRA

Thermal lens in Sapphire below 20 K

T. Tomaru *et al*., Classical and Quantum Gravity 19 (2002) 2045.

Magnitude of thermal lens : β / κ

Temperature coefficient of refractive index (β)

is at least 100 times smaller.

Thermal conductivity (κ) of sapphire at 20 K

is 10000 times larger

than that of fused silica at 300 K.

Magnitude of thermal lens is at least 10^6 times smaller.

No system for thermal lens compensation is necessary.

3. Other merits

Thermal lens in Silicon

In the case of (below) 20K, thermal lens is neglected.

In the case of 120K, less effective (careful investigation is necessary).

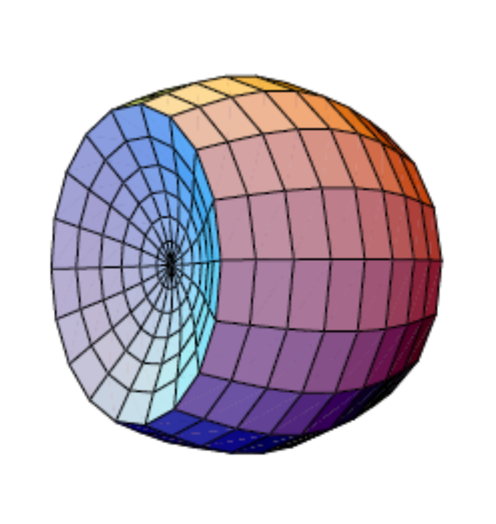
Temperature coefficient of refractive index (β) is comparable with that of fused silica at 300 K.

Thermal conductivity (κ) of silicon at 120 K is 1000 times larger.

Magnitude of thermal lens is 10^3 times smaller.

KAGRA

3. Other merits



Parametric instability

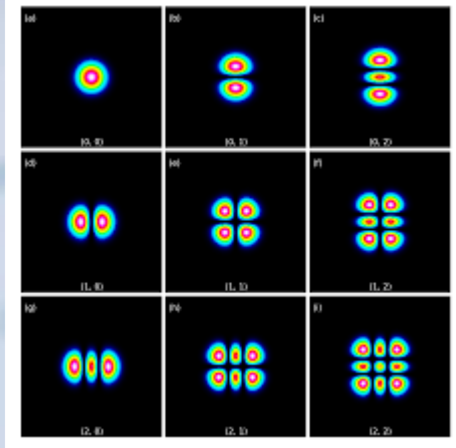
Radiation pressure

Optical mode in cavity

(**Large amplitude** of **other** (transverse) optical mode)

Elastic mode in mirror

(**Large vibration**)



Modulation

3. Other merits

Parametric instability of cryogenic interferometer is a less serious problem than that of room temperature.

K. Yamamoto *et al*., Journal of Physics: Conference Series 122 (2008) 012015.

(a) Number of unstable modes is smaller.

(b) More effective passive suppression of instability is possible.

3. Other merits

(a) **Number of unstable modes** is **smaller**.

Number of unstable modes is proportional to the **product** of **elastic** and **optical mode densities**.

Elastic mode density is inversely proportional to **cubic** of **sound velocity**.
Sound velocity in **sapphire** and **silicon** is about **twice times larger** than that in fused silica.

Elastic mode density of sapphire and silicon is **4 or 5 times smaller**.

3. Other merits

(a) Number of unstable modes is smaller.

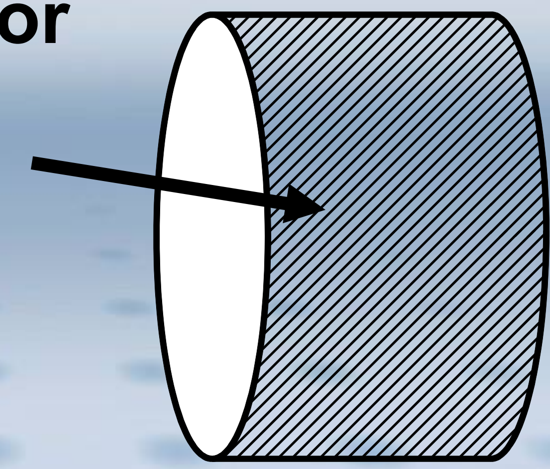
Number of unstable modes is proportional to the product of elastic and optical mode densities.

Optical mode density is smaller when beam radius is smaller.
Larger beam radius is one of techniques to reduce mirror thermal noise.
Cryogenic interferometer can adopt smaller beam because of small mirror thermal noise.

3. Other merits

(b) More effective passive suppression of instability is possible.

Passive suppression :
loss on barrel surface of mirror



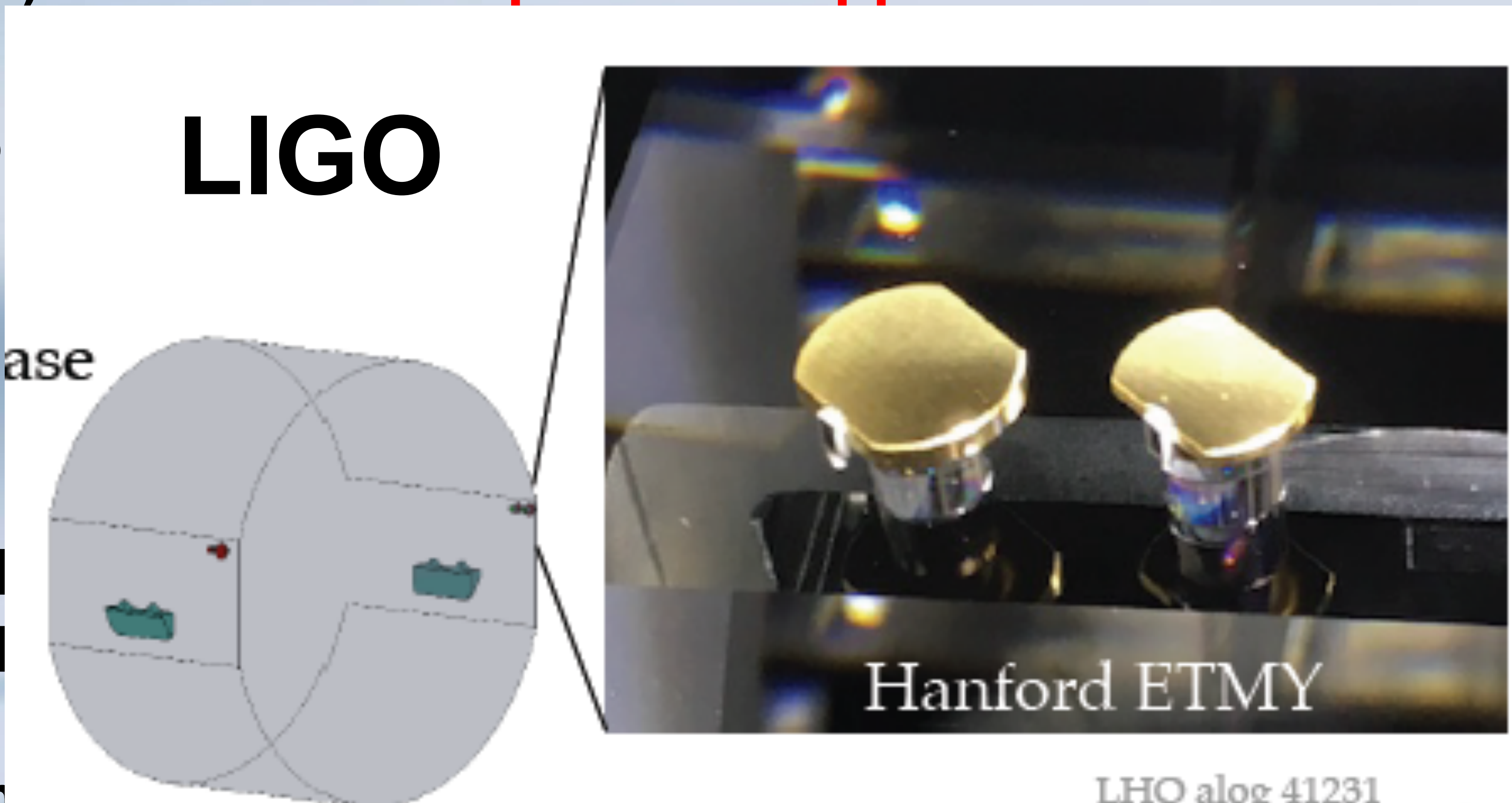
The increase of thermal noise should be taken into account.

In the case of cooled mirror, more effective suppression is possible.

3. Other merits

(b) More effective passive suppression

P



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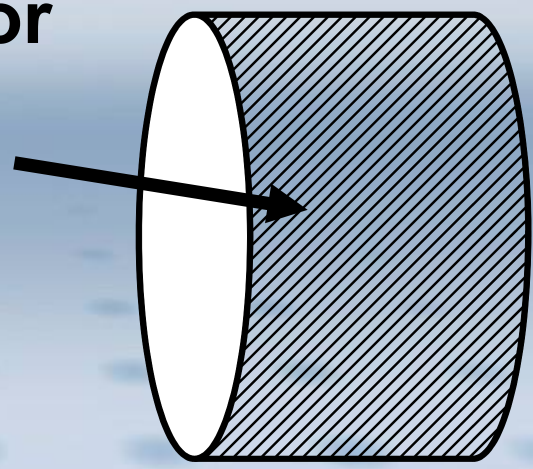
suppression is possible.

3. Other merits

(b) More effective passive suppression of instability is possible.

Passive suppression :

loss on barrel surface of mirror



The increase of thermal noise should be taken into account.

In the case of cooled mirror, more effective suppression is possible.

4. How to cool down

How to cool down actually ? (KAGRA bias …)

(1) Cooling bath (or something similar)

is necessary.

Cooling power is as large as possible.

(2) Temperature after cooling down is

as low as possible.

Heat load (except for mirror absorption)

must be negligible.

(120K operation; temperature adjustment system

is necessary. I skip this topic).

(3) Initial cooling time is as short as possible for long observation time.

4. How to cool down

(1) Cooling bath (or something similar)

Liquid helium, nitrogen …

Large cooling power

No vibration (after cool down)

120K : Only liquid nitrogen is necessary and reuse system is not necessary !

So, this could be a solution ….

4. How to cool down

(1) Cooling bath (or something similar)

Discussion in KAGRA (20K)

Reuse of helium (cycle of liquid and gas of helium):
Apparatus with high pressure is necessary.
It needs approval by government and license in Japan.
Cost of such apparatus is quite high and complicate.

Liquid helium in tunnel is not so fun ….

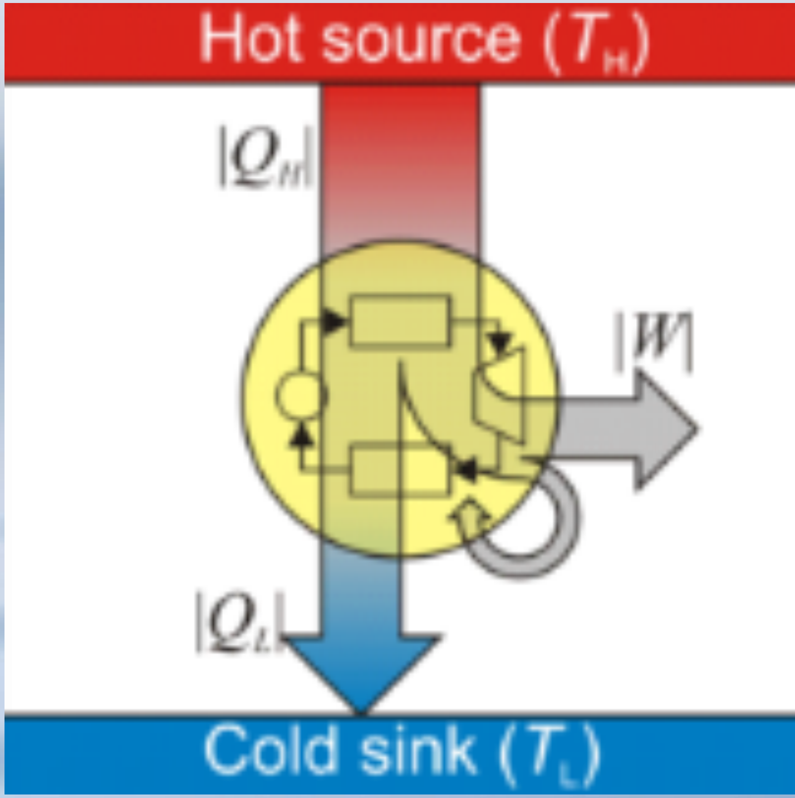
4. How to cool down

(1) Cooling bath (or something similar) for below 20K operation

Cryocooler !

Heat engine

Heat (Q) goes from hot to cold heat bath.
Part of heat (Q_H-Q_L) is converted into work(W).

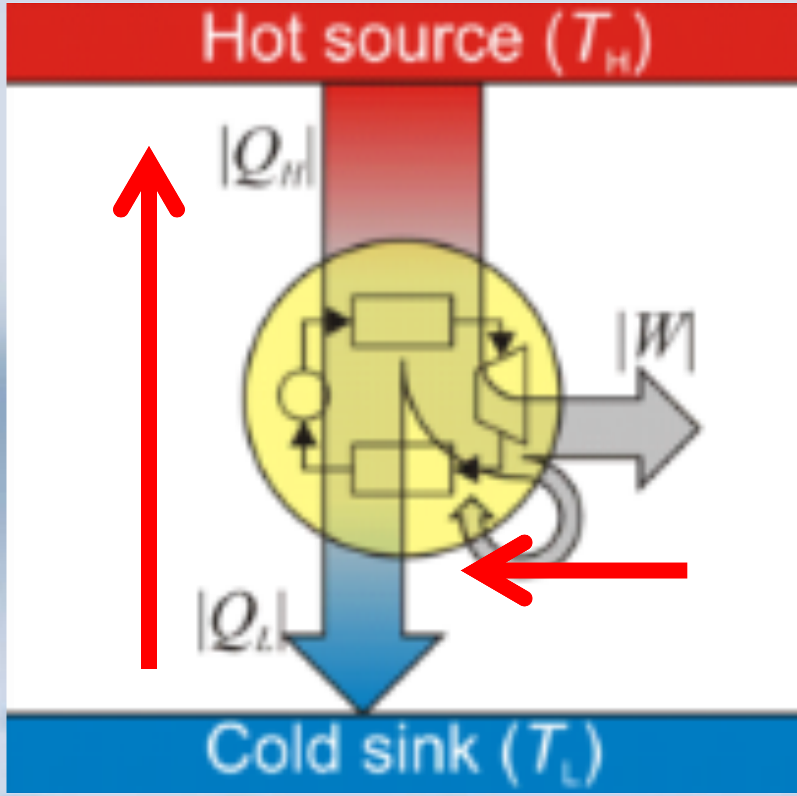


Wikipedia

4. How to cool down

(1) Cooling bath (or something similar) for below 20K operation

Cryocooler !
Work (W) is applied on cryocooler .
Heat (Q) goes from cold to hot heat bath.



Note : Efficiently (cooling power) at lower temperature is smaller because of second law of thermodynamics.

4. How to cool down

(1)Cooling bath (or something similar)

Cryocooler : Reverse operation of heat engine

(Rigid and heavy) Piston motion generates vibration.

Pulse tube cryocooler : “virtual” piston by valve unit.
This “virtual” piston consists of gas !
Small vibration is generated.

Pulse tube cryocooler : 50 W (above 60K)
1W (around 8 K)

C. Tokoku *et al*., CEC/ICMC2013, 2EPoE1-03, Anchorage, USA (2013).

4. How to cool down

KAGRA adopts pulse tube cryocooler. Vibration reduction system was developed by us.

T. Tomaru et al., Classical and Quantum Gravity 21 (2004) S1005.

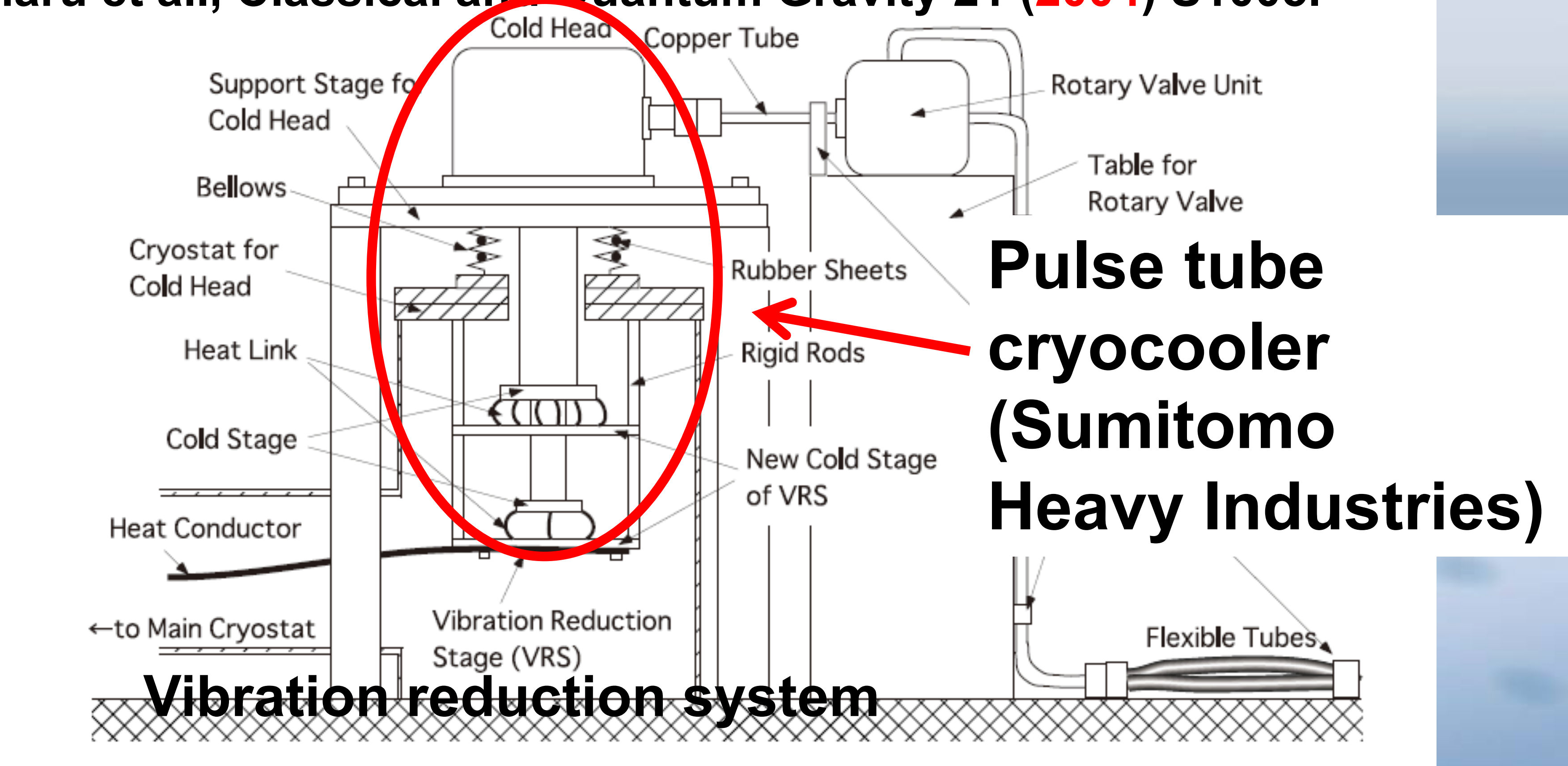
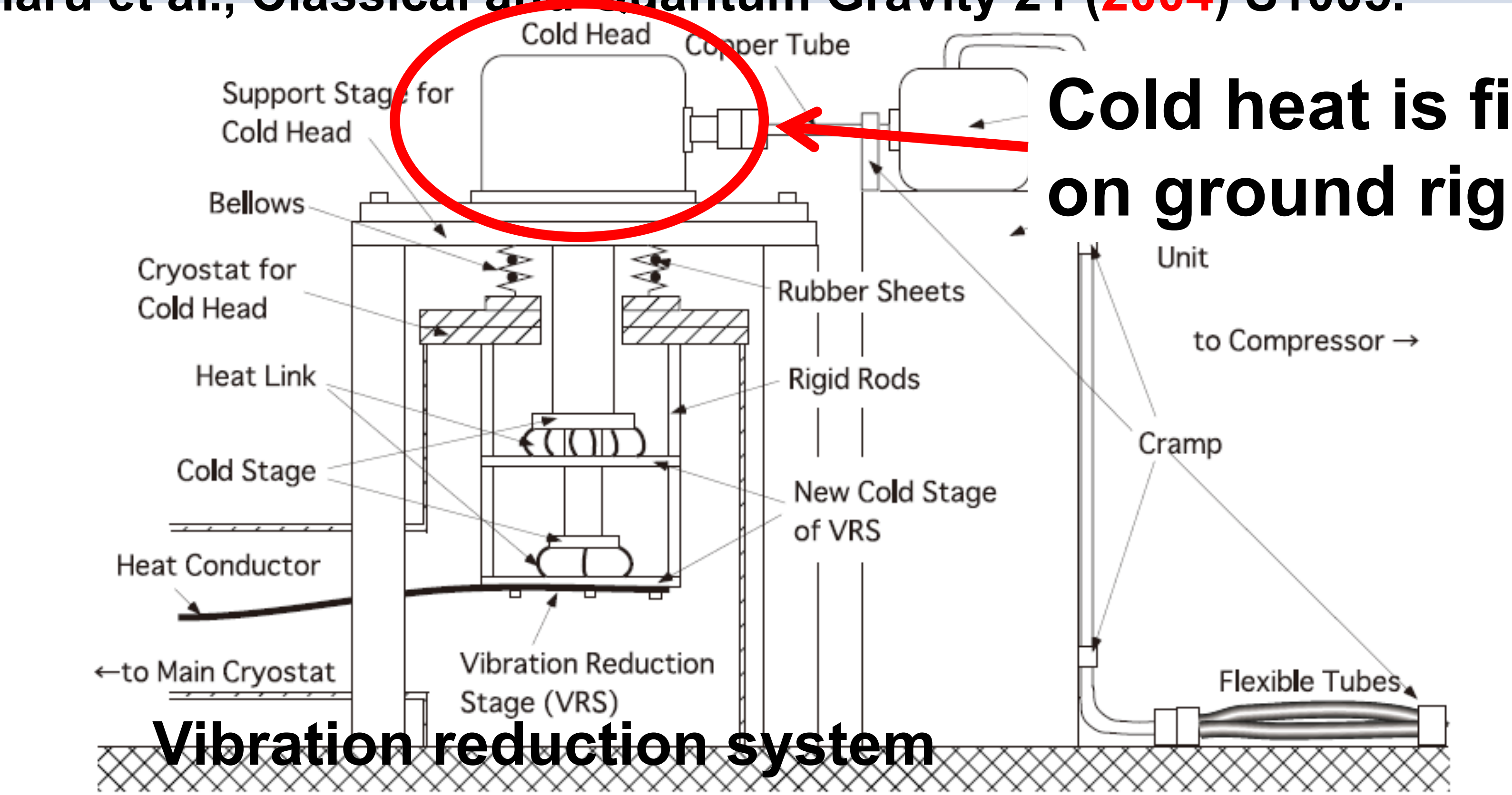


Figure 3. Vibration-reduction system we have been developing for the PT cryocooler.

4. How to cool down

KAGRA adopts pulse tube cryocooler . Vibration reduction system was developed by us.

T. Tomaru et al., Classical and Quantum Gravity 21 (2004) S1005.



Cold heat is fixed on ground rigidly.

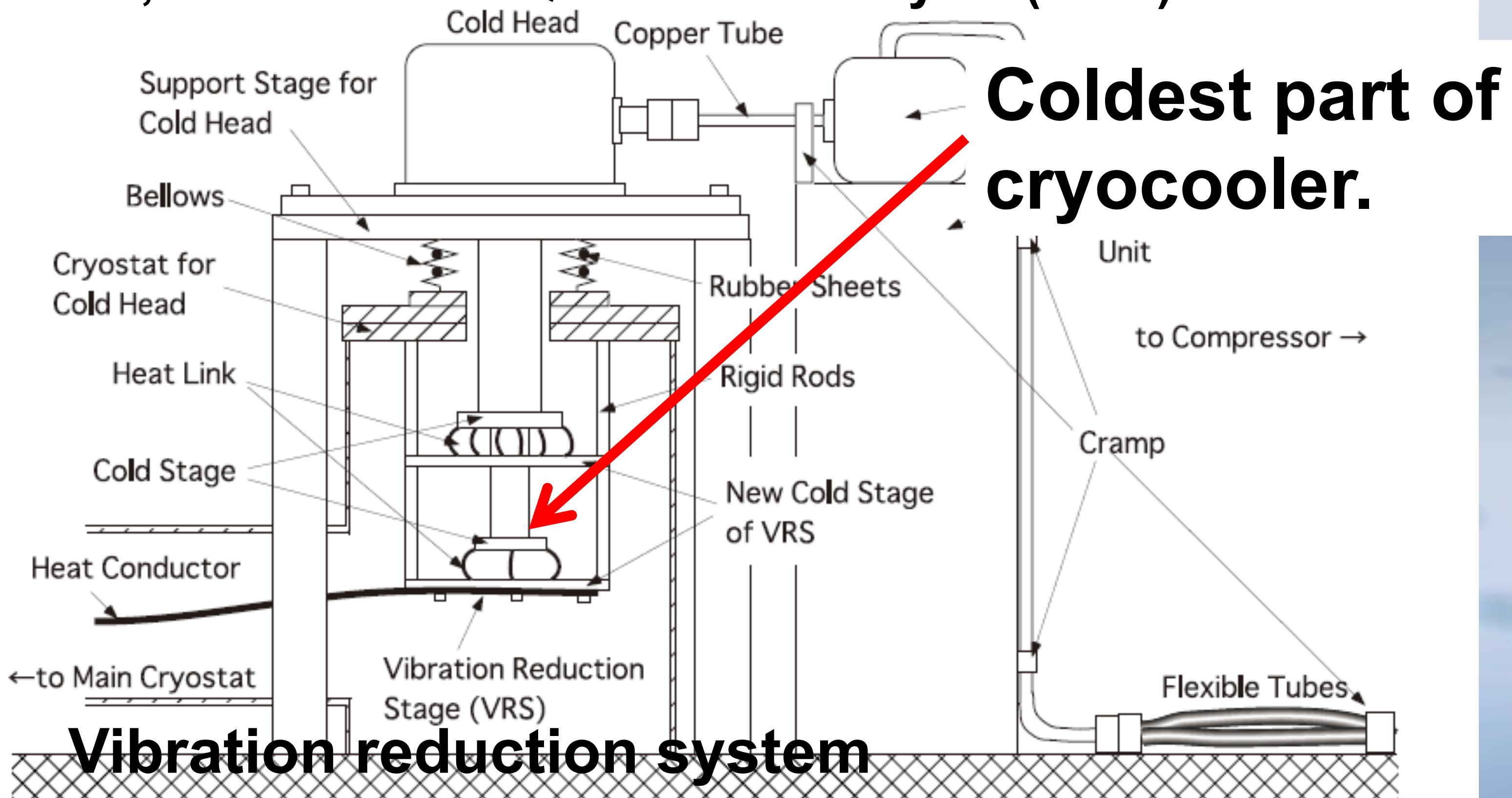
Vibration reduction system

Figure 3. Vibration-reduction system we have been developing for the PT cryocooler.

4. How to cool down

KAGRA adopts pulse tube cryocooler . Vibration reduction system was developed by us.

T. Tomaru et al., Classical and Quantum Gravity 21 (2004) S1005.



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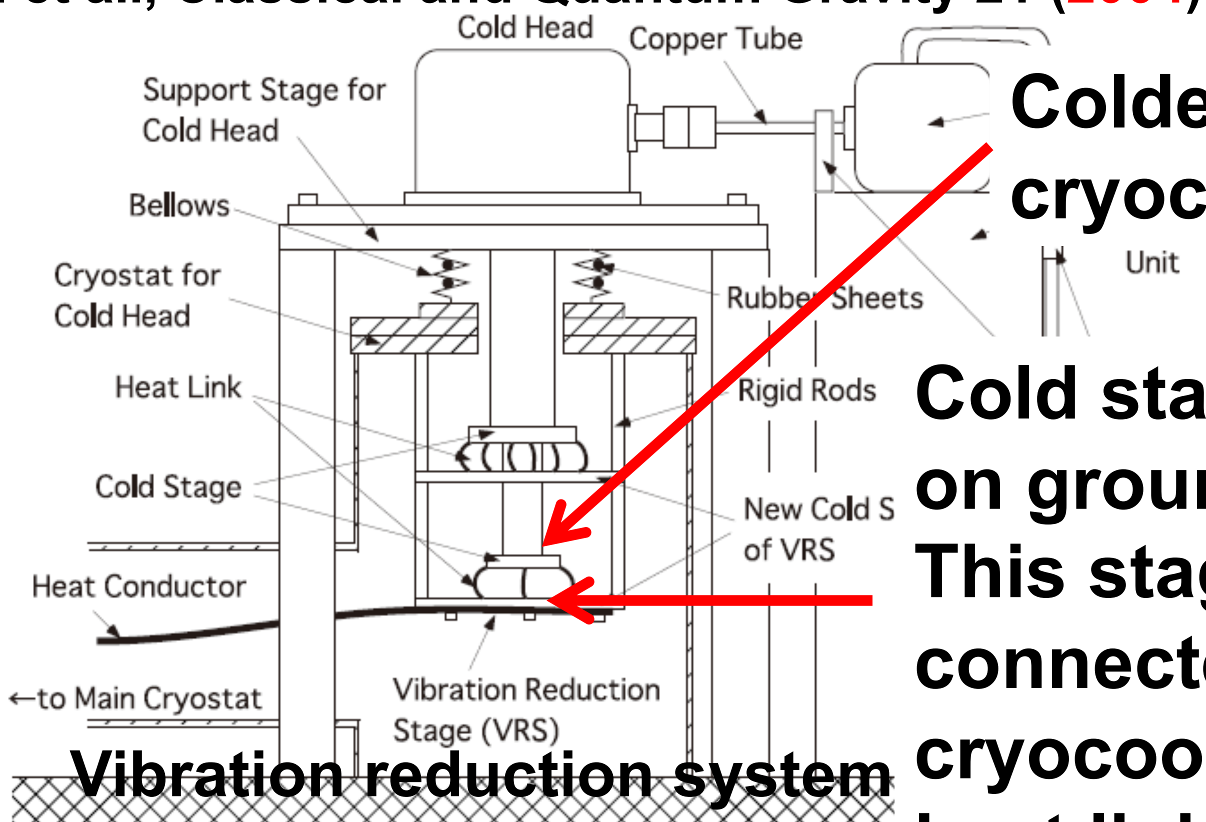


Coldest part of cryocooler.

Cold stage is fixed on ground rigidly. This stage is connected with cryocooler by soft heat links (Cu).

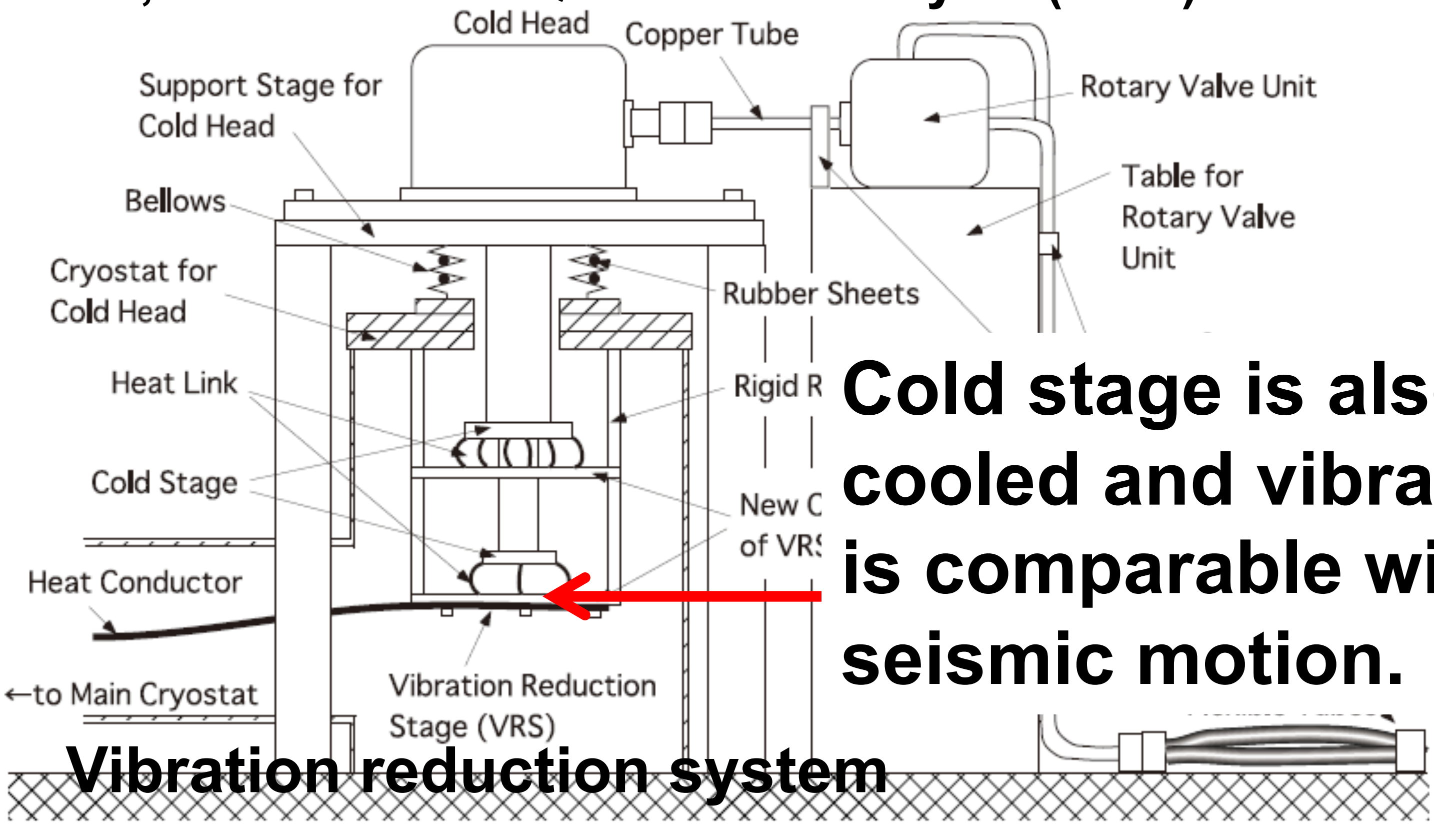
Vibration reduction system

Figure 3. Vibration-reduction system we have been d...

4. How to cool down

KAGRA adopts pulse tube cryocooler . Vibration reduction system was developed by us.

T. Tomaru et al., Classical and Quantum Gravity 21 (2004) S1005.



Cold stage is also cooled and vibration is comparable with seismic motion.

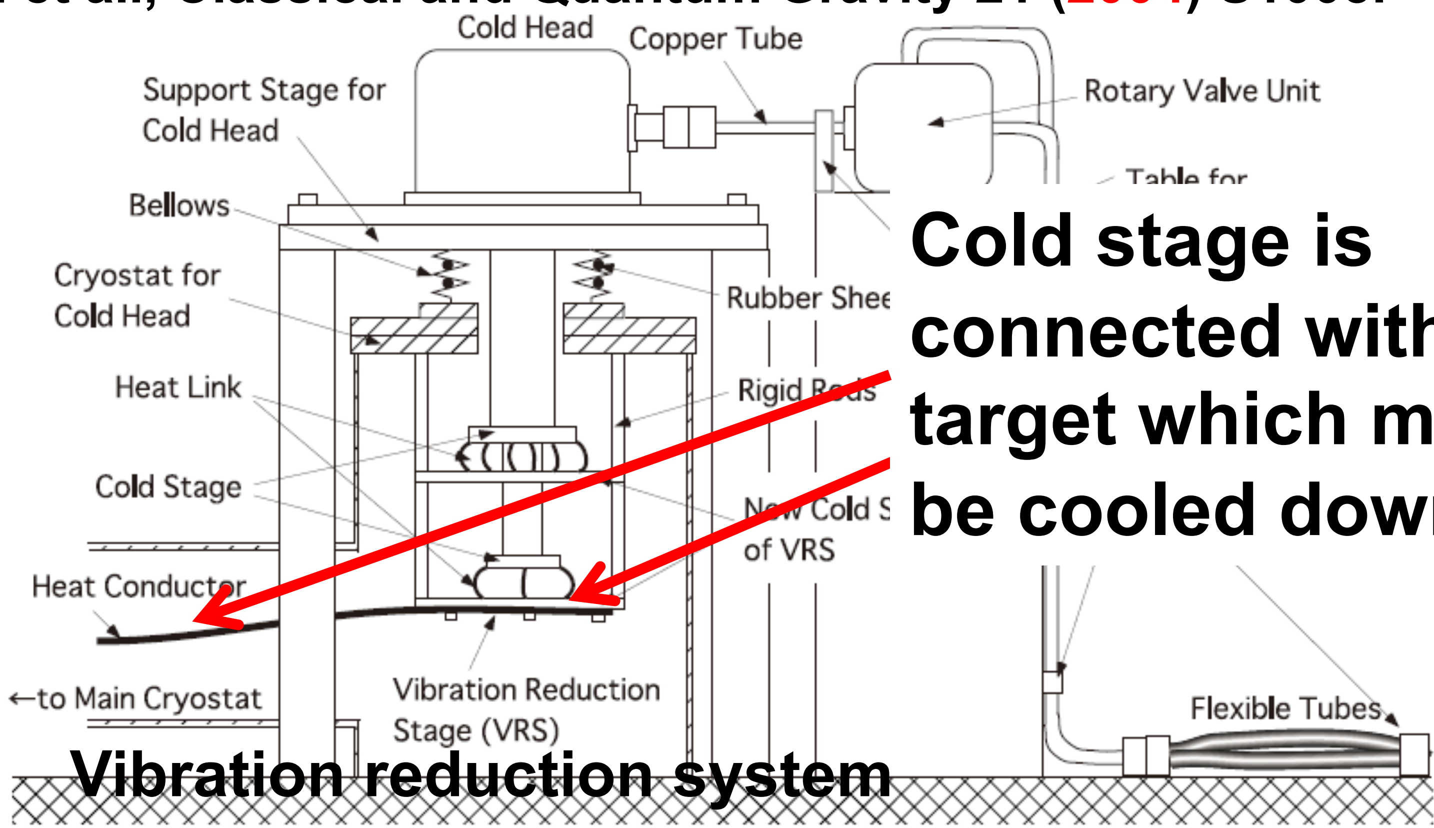
Vibration reduction system

Figure 3. Vibration-reduction system we have been developing for the PT cryocooler.

4. How to cool down

KAGRA adopts pulse tube cryocooler . Vibration reduction system was developed by us.

T. Tomaru et al., Classical and Quantum Gravity 21 (2004) S1005.



Cold stage is connected with target which must be cooled down.

Vibration reduction system

Figure 3. Vibration-reduction system we have been developing for the PT cryocooler.

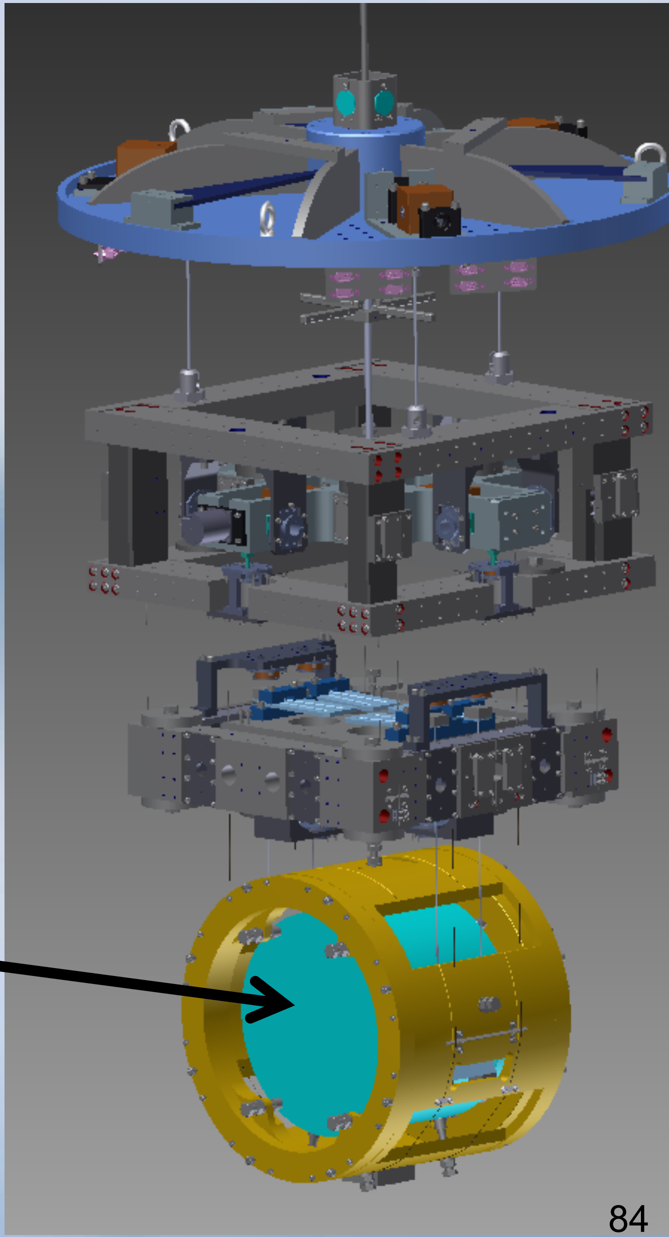
4. How to cool down

What is cooled down ?

We must cool not only mirrors and fibers but also …

(1) Cryogenic payload : Control of mirror position and alignment for light interference (high sensitivity).

K. Okutomi, Wednesday afternoon



4. How to cool down

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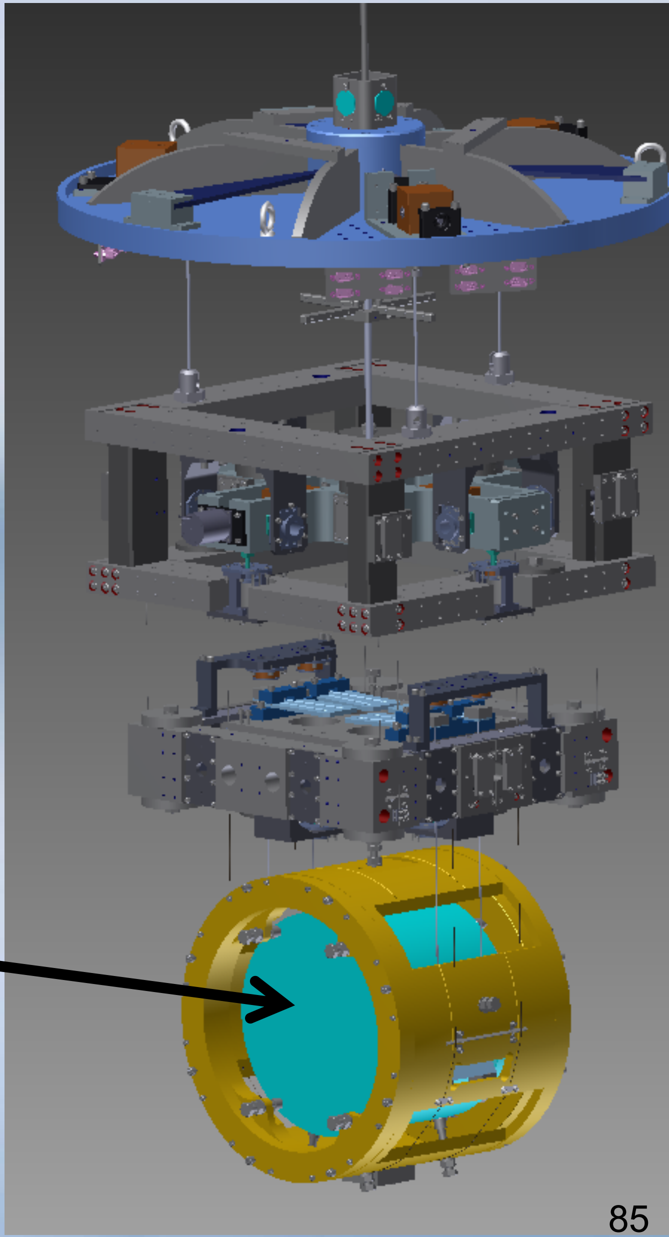


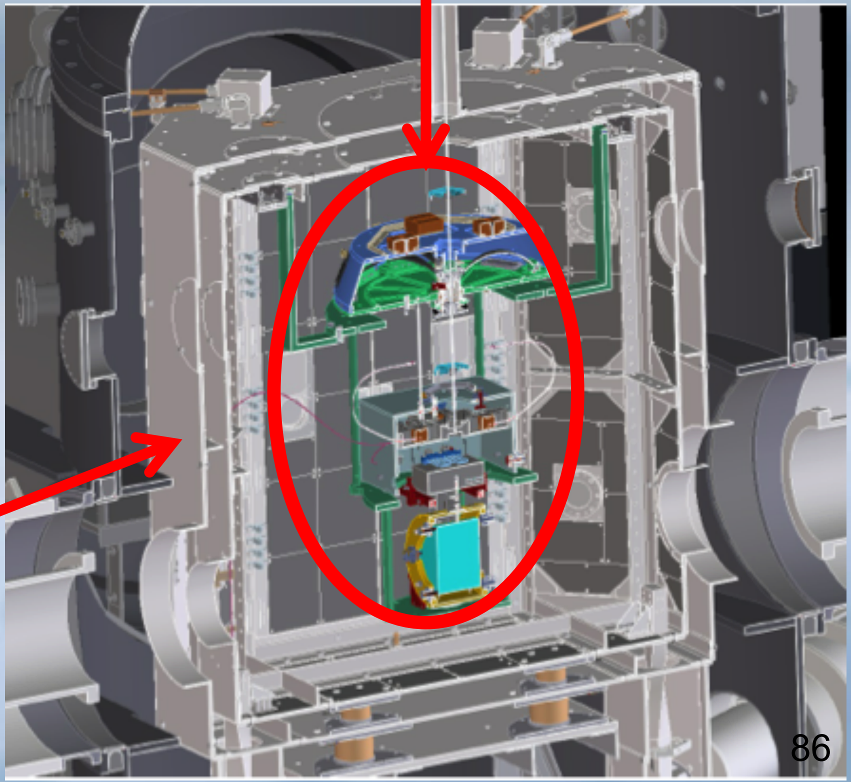
4. How to cool down

What is cooled down ?

We must cool not only mirrors and fibers but also …

(2) Radiation shield: Cooled wall to avoid attack of 300 K on cryogenic payload.

Cryogenic payload



Radiation shield

KAGRA

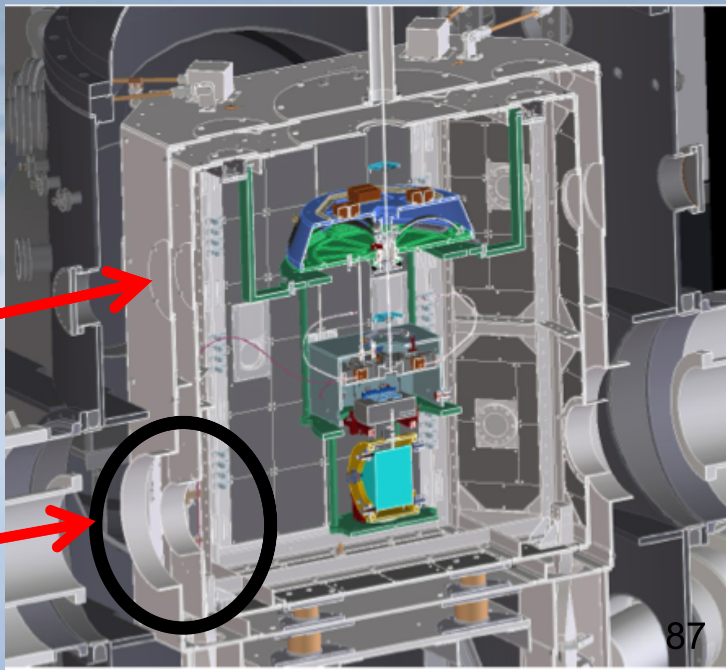
4. How to cool down

(2)Small heat load

Actually, extra heat load is always issues …

Largest one : 300K radiation through hole for laser beam. This hole is comparable with mirror itself; 20cm in diameter. 300K radiation is about 20 W !

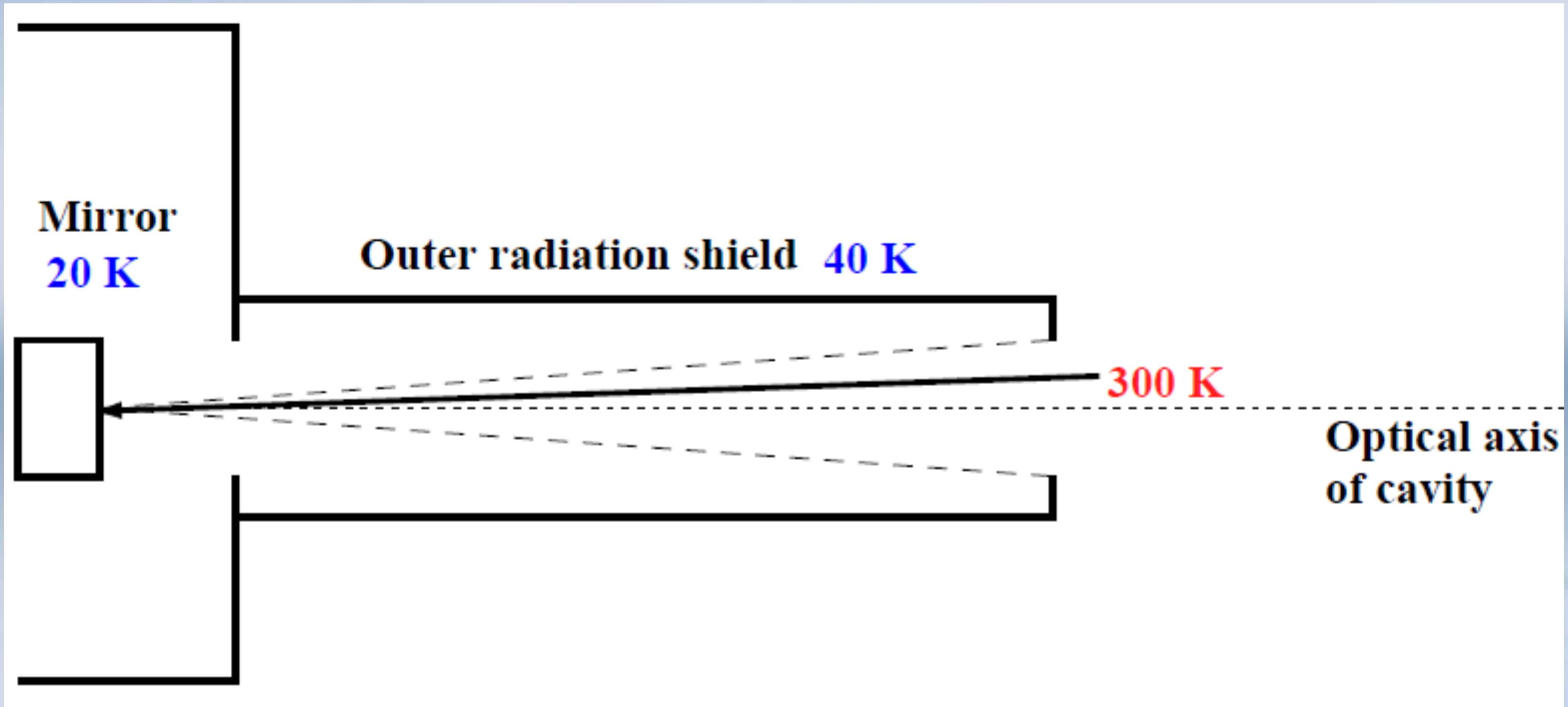
It is larger than cryocooler power around 8K!



Radiation shield

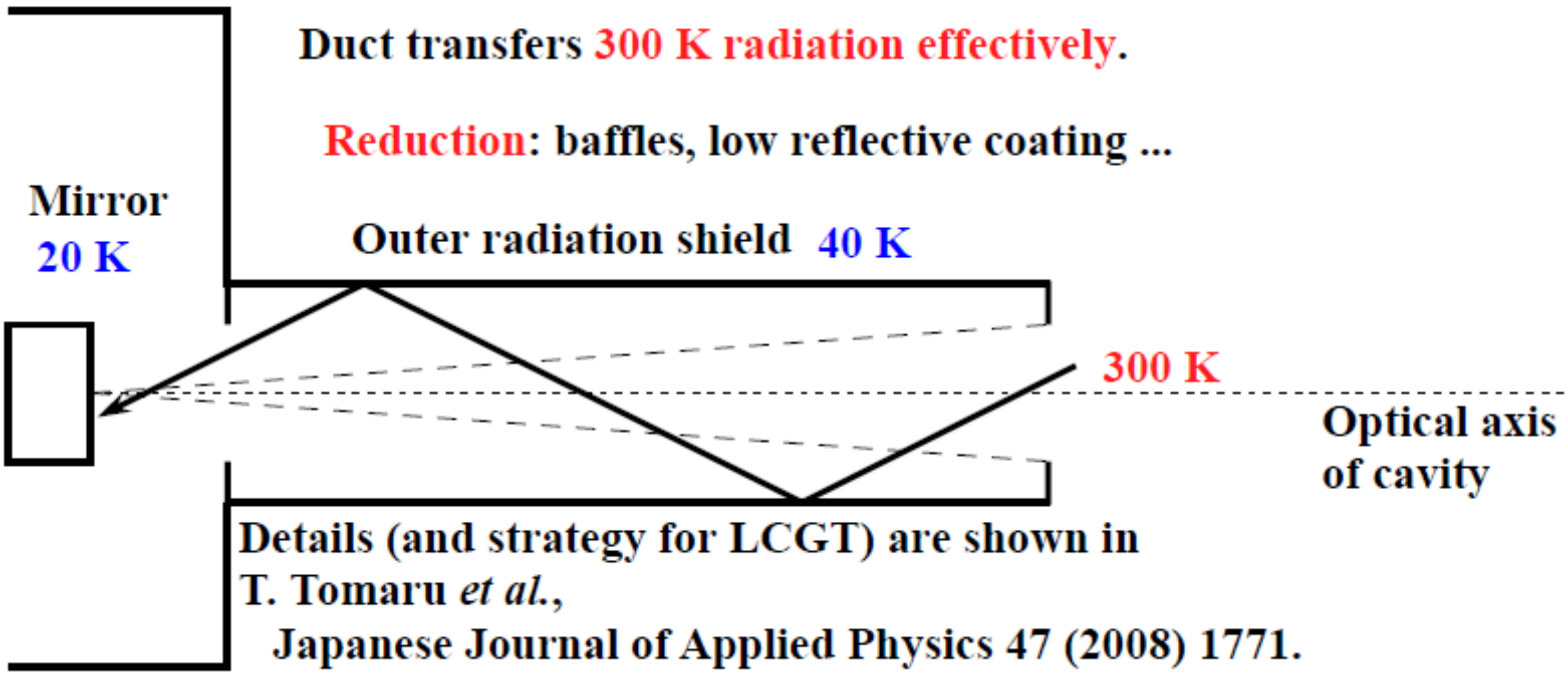
Hole for laser beam

4. How to cool down



Power of 300K radiation is proportional to solid angle of hole. So, 300 K radiation should be small. But actually,…..

4. How to cool down



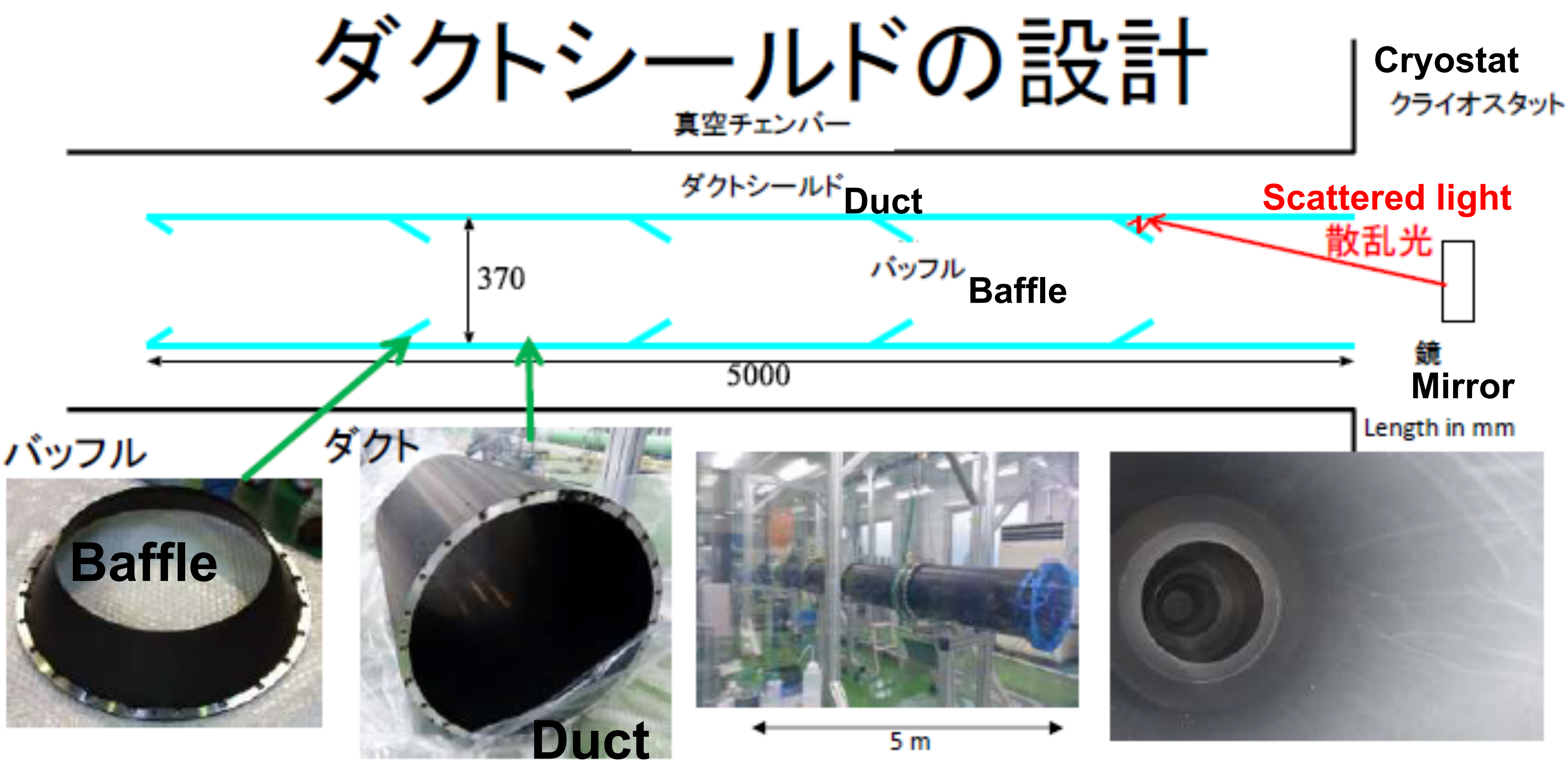
T. Tomaru et al.,
Journal of Physics:Conference Series 122 (2008) 012009.

But actually, cryo duct can transmits 300K radiation well (!) because inner surface of cryo duct reflects radiation !

4. How to cool down

Cryo duct for KAGRA

Y. Sakakibara, Ph.D. thesis (2015).



Black coating on inner surface and baffles

Only 0.1 W radiation can pass through.

4. How to cool down

(3)Initial cooling time

It is always serious issue in cryogenic experiment.
KAGRA case is introduced.

(a)Initial cooling of radiation shield
Otherwise, mirror can not be cooled !
(b)Initial cooling of mirror and its suspension (cryogenic payload)
It is isolated thermally !
(c) How to reduce cooling time

4. How to cool down

(a) Initial cooling of radiation shield

In the case of KAGRA

Total mass of inner radiation shield is about 700 kg.
C. Tokoku *et al*., CEC/ICMC2013, 2EPoE1-03, Anchorage, USA (2013).

Typical specific heat : 1000 J/Kg/K at 300K
Dulong-Petit law

4. How to cool down

(a) Initial cooling of radiation shield

Heat extraction power
Pulse tube cryocooler : 100 W (above 60K)
in KAGRA (two cryocoolers).
C. Tokoku *et al.*, CEC/ICMC2013, 2EPoE1-03, Anchorage, USA (2013).

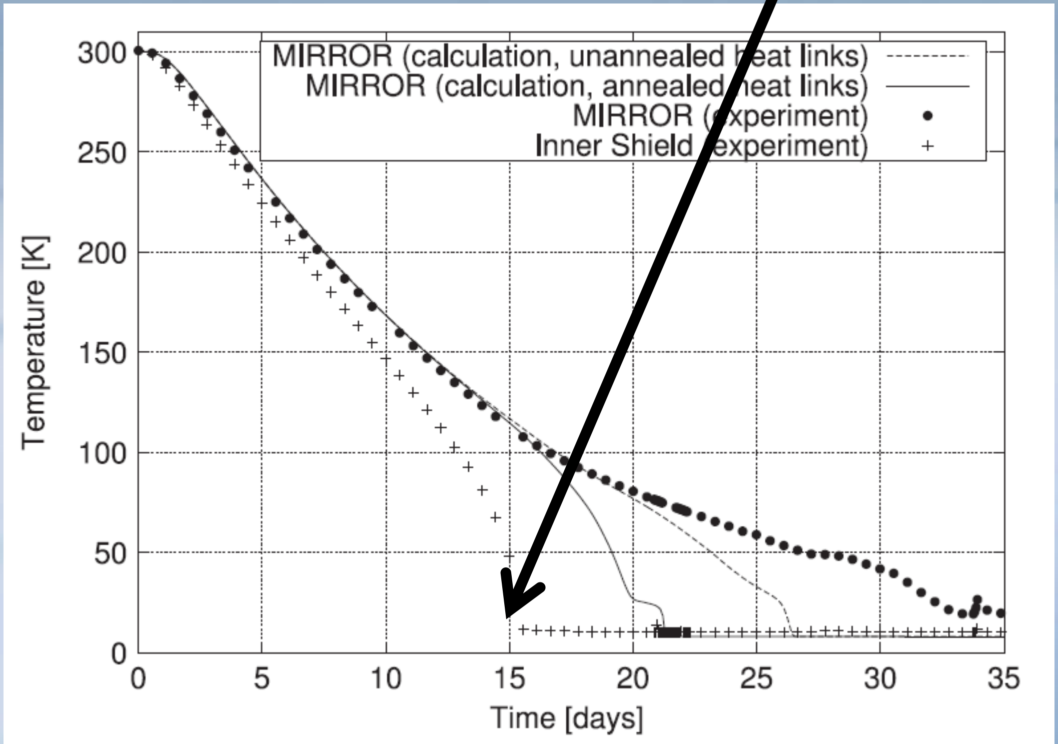
Calculation shows that it takes about 14 days to cool down (from 300K to 100K).
Below 100K, cooling time is quite small because of small specific heat (and large thermal conductivity in some case).
Debye model (Specific heat is proportional to cubic of temperature.)

4. How to cool down

(a) Initial cooling of radiation shield

Experiment showed that it takes 15 days to cool the radiation shield.

Y. Sakakibara *et al*., Classical and Quantum Gravity 31(2014)224003.



4. How to cool down

(b) Initial cooling of cryogenic payload
Payload is isolated thermally.

In the case of KAGRA,
Total mass of payload is 200 kg.
Typical specific heat : 1000 J/Kg/K at 300K

Dulong-Petit law

4. How to cool down

(b) Initial cooling of cryogenic payload

Cooling payload above 100 K

Black body radiation

KAGRA : Total surface area of payload is 1 m^2.

Radiation power is 460W at most (black coating is necessary) when radiation shields were cooled down.

It takes only 1 day to cool down cryo payload if radiation shields suddenly cooled !

4. How to cool down

(b) Initial cooling of cryogenic payload

Cooling payload above 100 K

Thus, temperature of payload is comparable with that of radiation shield while the payload temperature is above 100K.

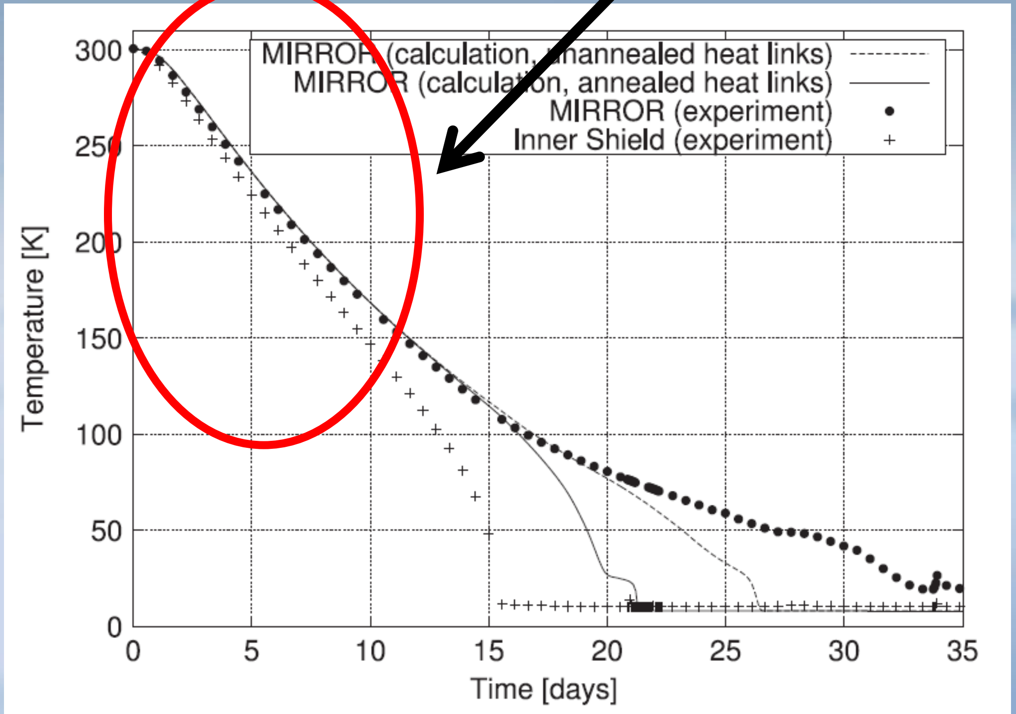
In the case of Silicon at 120K, this is end of story.

4. How to cool down

(b) Initial cooling of cryogenic payload

KAGRA : Temperature of payload is comparable with that of radiation shield.

Y. Sakakibara *et al*., Classical and Quantum Gravity 31(2014)224003.



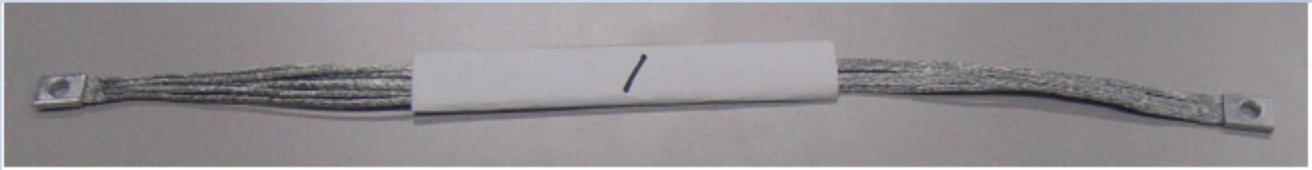
4. How to cool down

(b) Initial cooling of cryogenic payload

Cooling payload below 100 K (in the case of below 20K!)

Radiation does not work (T^4).

In the case of KAGRA,
Heat links (twisted thin Al fibers) between payload and cryocoolers.
Thermal conductivity of Al is around 10 K is 10000W/m/K.



アルミ撚り線7本並列（0.15mm×49本×7列） 30cm, 40cm, 50cm

4. How to cool down

(b) Initial cooling of cryogenic payload

Cooling payload below 100 K

Designed heat link can transfer 1W heat power (mirror heat absorption is 1 W).

Specific heat is smaller at lower temperature.

Debye model (Specific heat is proportional to cubic of temperature.)

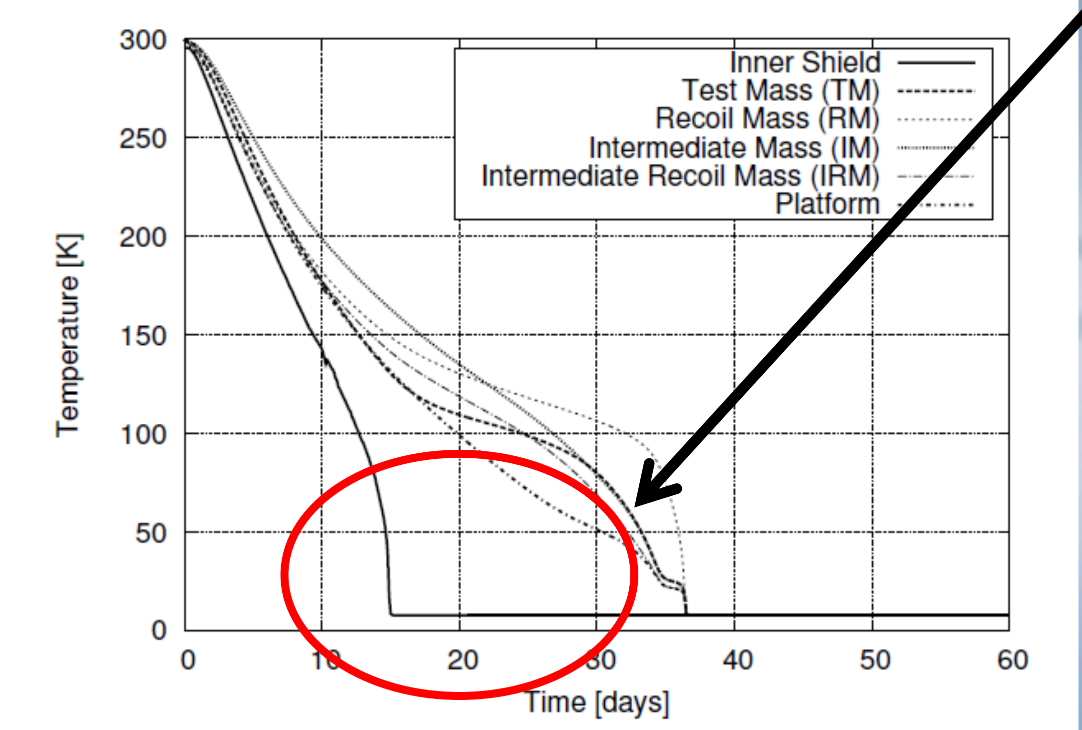
Typical specific heat : 300 J/Kg/K at 100K
KAGRA : Total mass of suspension is 200 kg.

4. How to cool down

(b) Initial cooling of cryogenic payload

Cooling payload below 100 K
When power of heat extraction is 1W,
the cooling time is 15 days.

Y. Sakakibara *et al*., CEC/ICMC2013, 2EOrD4-03, Anchorage, USA (2013).



4. How to cool down

(c) How to reduce cooling time

(i)Short cooling of radiation shield in any cases
Payload temperature can follow
shield temperature above 100 K
owing to radiation.

(ii)Short cooling of payload below 100K
It is not necessary in the case of 120K.
Y. Sakakibara, Ph.D. thesis (2015).

4. How to cool down

(c) How to reduce cooling time

(i)Short cooling of radiation shield

Much more cryocoolers ?
(KAGRA : 2 cryocoolers for inner shield
2 cryocoolers for payload)
Geometrical constrain, vibration

More powerful cryocoolers ?
Development, vibration

4. How to cool down

(c) How to reduce cooling time

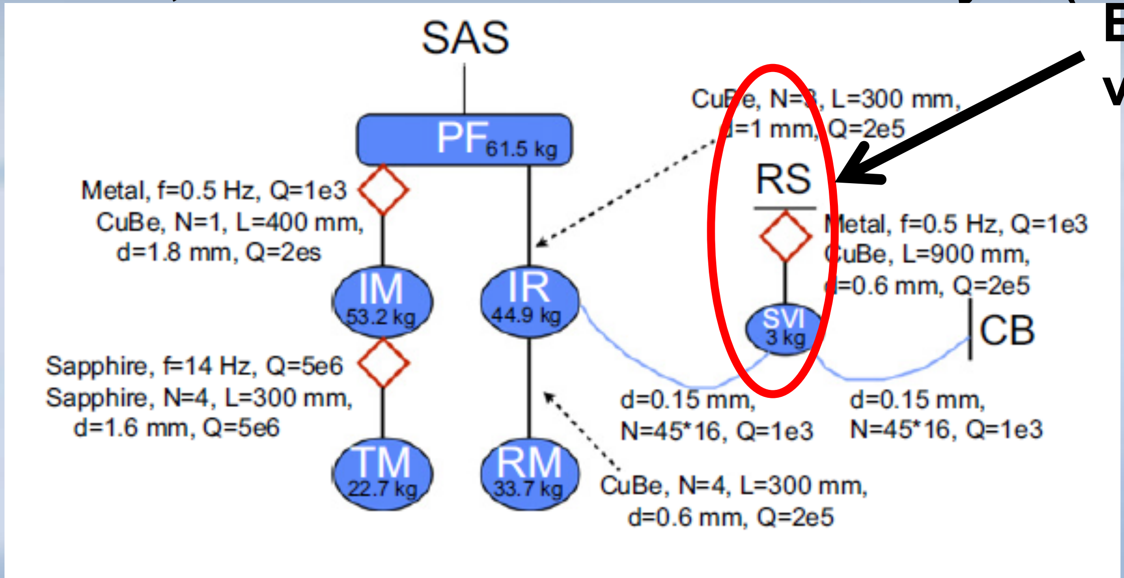
(ii)Short cooling of payload below 100K

Thicker and **shorter** heat links

Issue is **external vibration transmission**.

KAGRA needs extra **vibration isolation system for heat links**.

D. Chen *et al*., Classical and Quantum Gravity 31(2014)224001.



Extra pendulum for vibration isolation

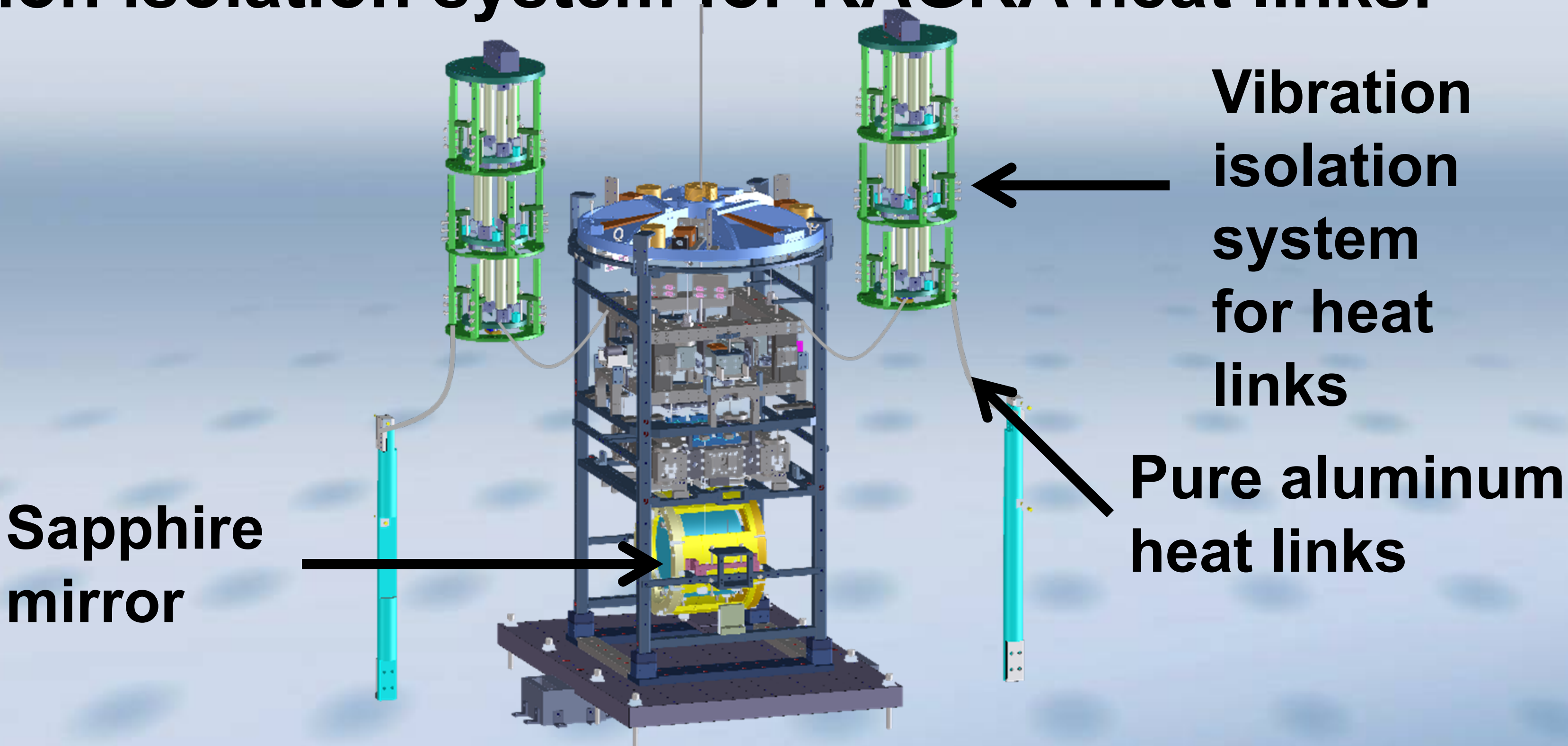
4. How to cool down

(c) How to reduce cooling time

(ii)Short cooling of payload below 100K

Thicker and shorter heat links

Vibration isolation system for KAGRA heat links.



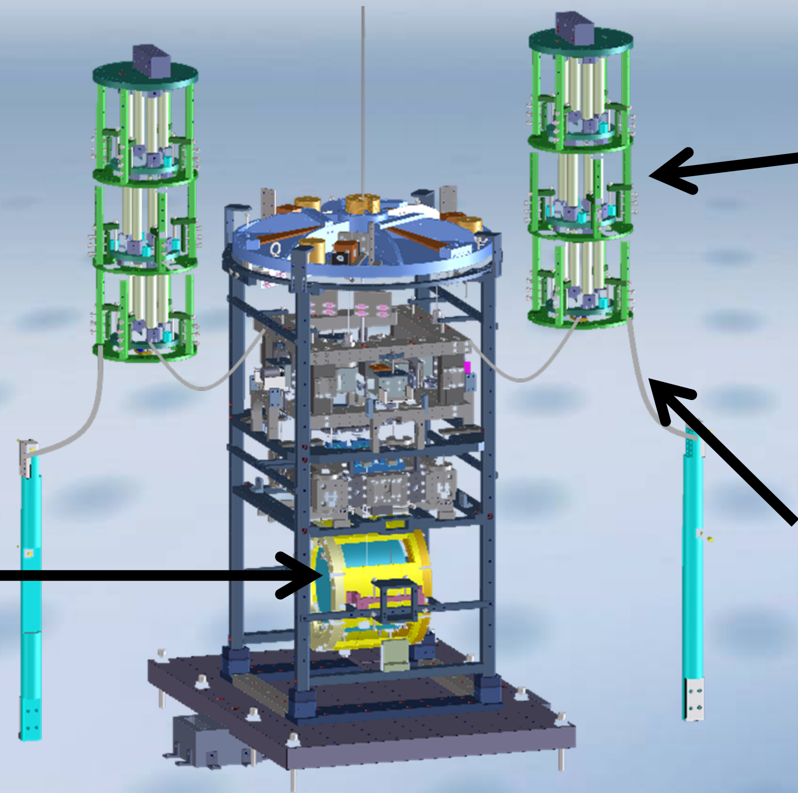
T. Yamada et al., https://gwdoc.icrr.u-tokyo.ac.jp/cgi-bin/private/DocDB/ShowDocument?docid=9002

4. How to cool down

(c) How to reduce cooling time

(ii)Short cooling of payload below 100K

If you develop better heat link vibration isolation system that that of KAGRA, you can adopt thicker and shorter heat links and initial cooling times is shorter.



4. How to cool down

(c) How to reduce cooling time

(ii)Short cooling of payload below 100K

Heat path with thermal switch

Initial cooling : Thermal switch is turned on. Heat path works.

After cooling down : Thermal switch is turned off. Heat path is cut.

Thermal switch is quite tricky part ….

4. How to cool down

(c) How to reduce cooling time

(2)Short cooling of payload below 100K

Heat path with thermal switch

Gas : Radiation shield should keep gas.

All holes for laser beam and bar from room temperature part are closed.

During cooling, main laser beam can not observe drift of mirror.

Super insulator absorbs helium gas.

It takes longer time to evacuate helium gas.

4. How to cool down

(c) How to reduce cooling time

(2)Short cooling of payload below 100K

Heat path with thermal switch

Mechanical thermal switch

between payload and crycoolers

Large heat contact during initial cooling (force)

Large thermal isolation after initial cooling

(soft metal for contact disturbs detachment)

Thermal switch on suspended object

Direction and position of mirror should be changed after this switch is turned off.

Mechanism must work at cryogenic temperature.

5.Summary

Merits of cryogenic interferometer
(Comparison with 300K interferometer)

(1) Small mirror (coating) thermal noise
(2) Small thermal lens
(3) Less serious parametric instability

Challenges
(1) New martials (sapphire, silicon) as substrate
(2) Small vibration cooling bath or cryocoolers
(3) Cryoduct to terminate 300K radiation
(4) Shorter cooling time of radiation shield

5.Summary

Operation temperature

Below 20K operation

We can enjoy merits fully.

What we must investigate or overcome

(1) Thicker fiber for heat transmission

(2) Heat link vibration isolation

(3) Cooling time below 100K

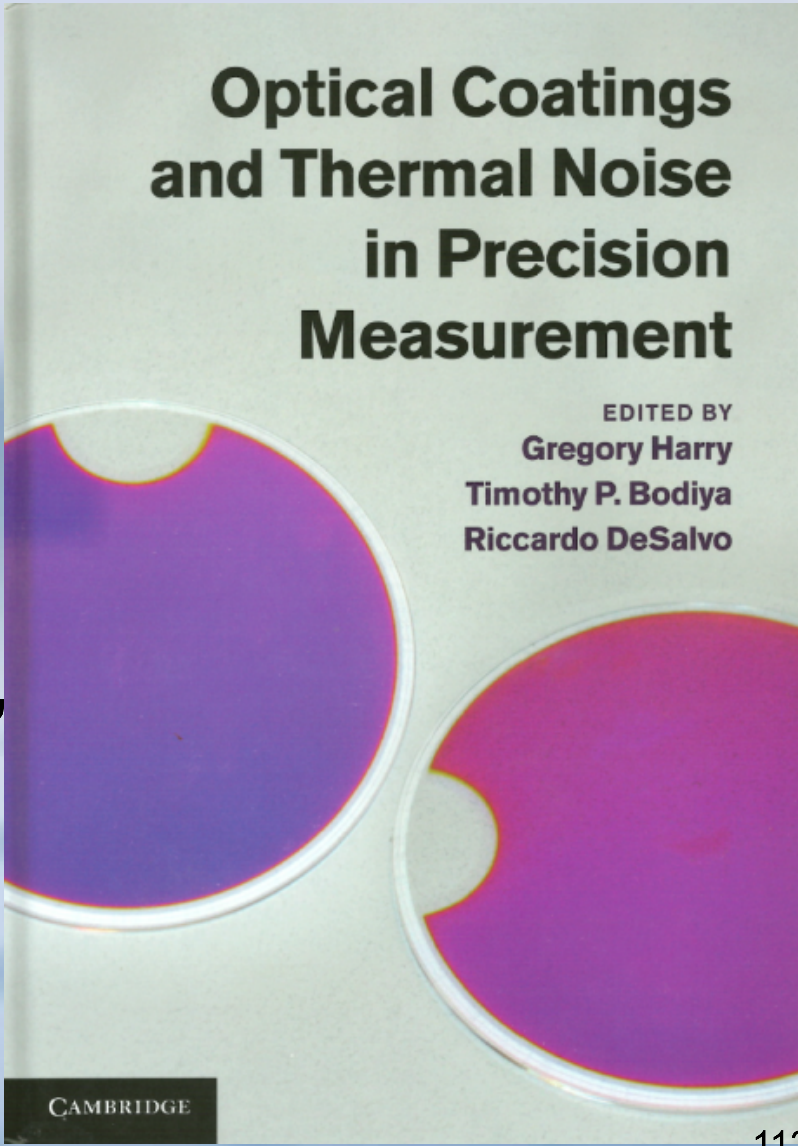
120K operartion

Since radiation cooling is effective, issues below 20K does not matter. But some merits are missed … (Coating mechanical loss reduction is necessary).

The book about coating thermal noise was published on 2012 !

Cambridge University Press

Chapter 8 (K. Numata and K. Yamamoto) “Cryognics”



Thank you for your attention !

1.Introduction

	aLIGO / AdV	A+/V+	KAGRA	CE 1	CE 2	ET-LF	ET-HF
Arm Length [km]	4 / 3	4	3	40	40	10	10
Mirror Mass [kg]	40 / 42	40	23	320	320	211	200
Mirror Material	silica	silica	sapphire	silica	silicon	silicon	silica
Mirror Temp [K]	295	295	20	295	123	10	290
Suspension Fiber	0.6m/0.7m SiO2	0.6m SiO2	0.35m Al2O3	1.2m SiO2	1.2m Si	2m Si	0.6m SiO2
Fiber Type	Fiber	Fiber	Fiber	Fiber	Ribbon	Fiber	Fiber
Input Power [W]	125	125	70	150	220	3	500
Arm Power [kW]	710 / 700	750	350	1400	2000	18	3000
Wavelength [nm]	1064	1064	1064	1064	1550	1550	1064
NN Suppression	1	1	1	10	10	1	1
Beam Size [cm]	(5.5/6.2) / 6	5.5/6.2	3.5/3.5	12/12	14/14	9/9	12/12
SQZ Factor [dB]	0	6	foreseen	10	10	10	10
F. C. Length [m]	none	300	unknown	4000	4000	10000	500

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2. Thermal noise

In the case of KAGRA (Sapphire, 20K) ….